Princeton Center for Heliophysics
Heliophysics Seminar
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# Solar Wind Turbulence: in-situ observations from magneto-fluid to kinetic plasma scales

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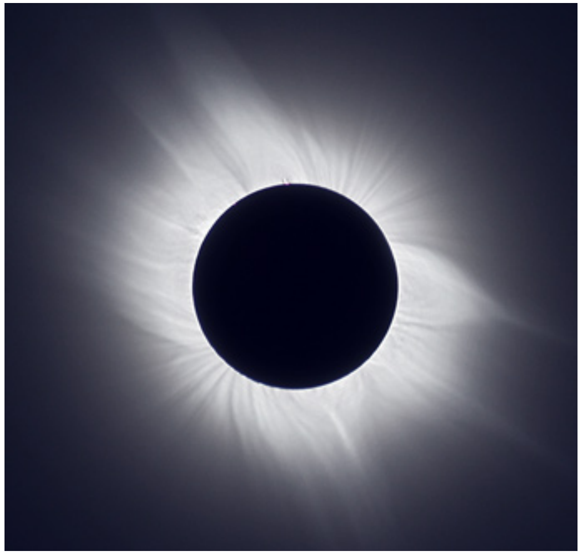
# The solar wind

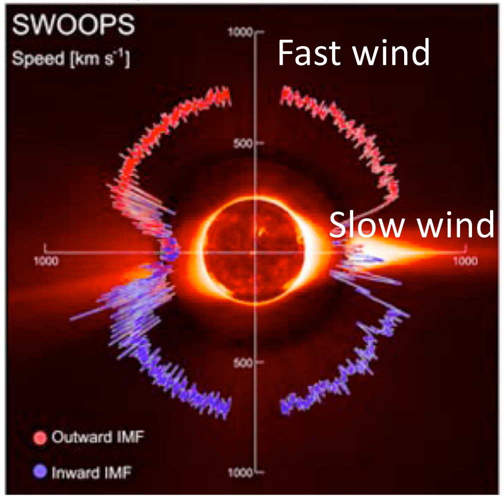
- Expansion of the solar corona in interplanetary space
- Best natural laboratory of astrophysical plasmas, which can be explored with space missions



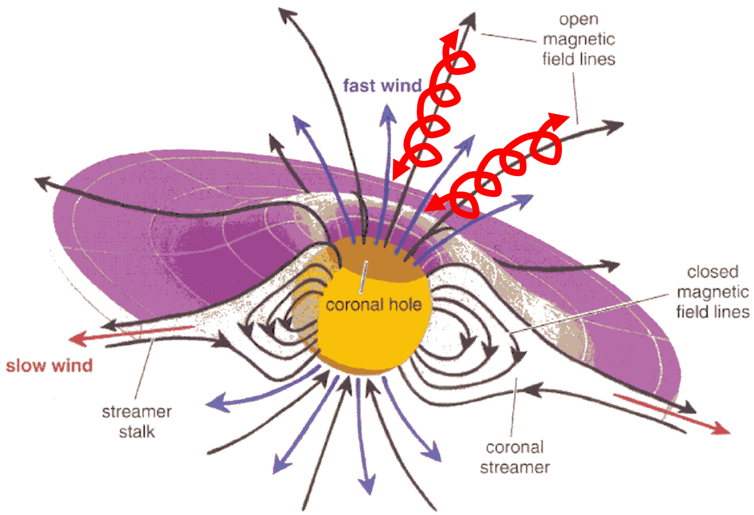
- Essentially electrons and protons (~5% of heavier ions)
- Supersonic and superalfvénic in interplanetary space (mean speed ~500 km/s)
- Mean temperature ($e^-$,$p^+$) at 1 AU ~20 eV
- Mean density at 1 AU ~5 $cm^{-3}$
- Few collisions (1 collision/1 AU) ⇒ viscosity ~ 0 ⇒ magnetic field is frozen in plasma

# Interplanetary magnetic field

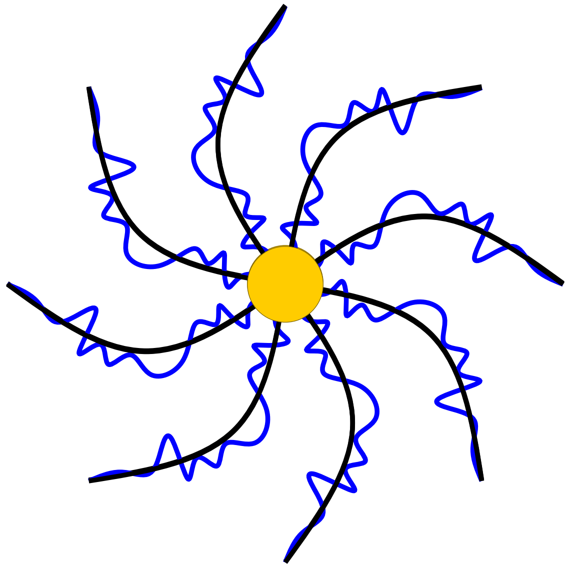
Ulysses First Orbit




[McComas et al., GRL, 1998]




Parker Spiral



Magnetic field is turbulent

# Turbulence?

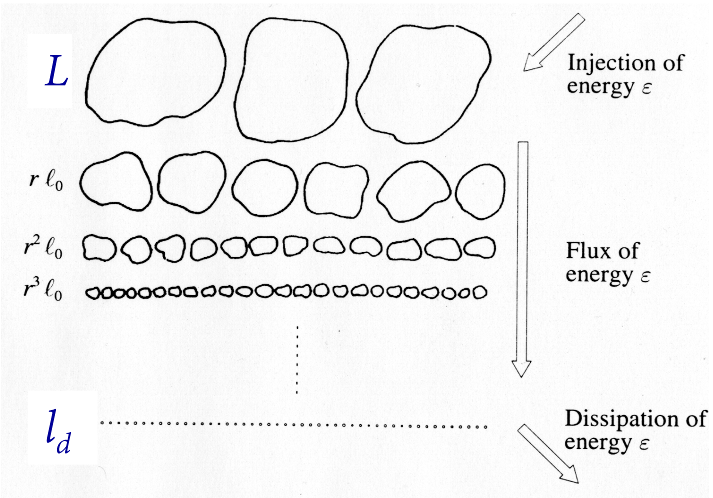
Leonardo da Vinci,
Studies of water (1510-1512)

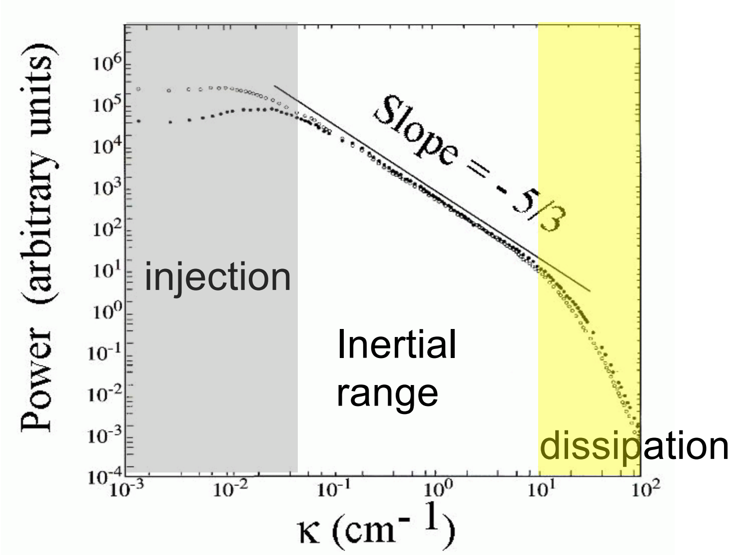
The fall of a stream of water from a sluice into a pool

Locally unpredictable, but **statistical properties are predictable and universal**

Energy cascade in the Fourier space (Kolmogorov, 1941):

- velocity field energy has **a universal spectrum ~ $k^{-5/3}$**
- **inertial range**: scale invariance, same physics at all scales $l$



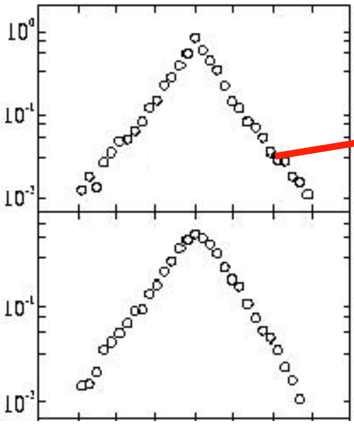
# Intermittency in fluid turbulence

- Scale dependent non-Gaussianity of turbulent fluctuations
- Appearance of coherent structures

PDF($\delta v$)

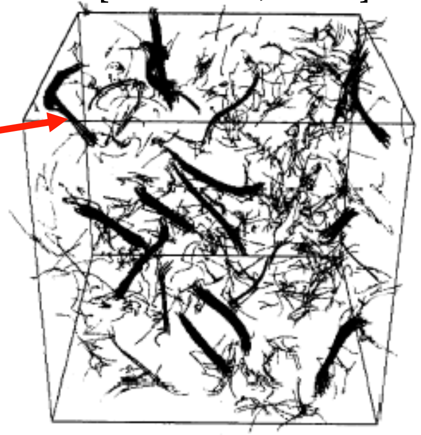
Small scale

Large scale

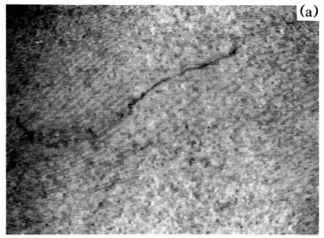


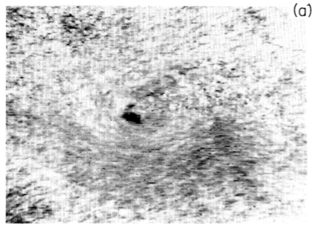

$\delta v_l = v(r+l) - v(r)$

[She et al., 1991]



[S. Douady, Y. Couder, and M. E. Brachet, PRL, 1991]

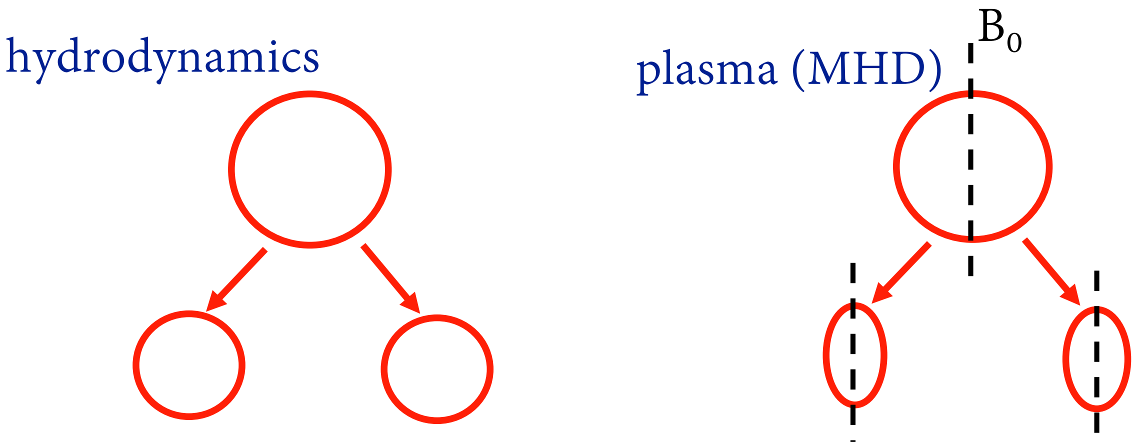



**Filaments of vorticity** (3D HD simulations & observations)

- length ~ $L_{injection}$ (L)
- cross-section ~ $L_{dissipation}$ ($l_d$)

# Turbulence in space plasmas

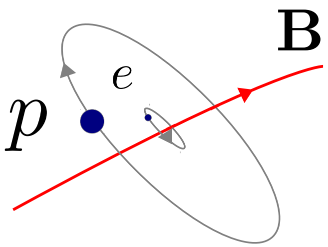



1. Presence of a mean magnetic field $B_0$ ⇒ anisotropy of turbulent fluctuations
2. Plasma waves: Alfvén, magnetosonic, mirror, whistlers, kinetic Alfvén waves (KAW), etc… (wave turbulence)
3. Nearly no collisions : mean free path ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

$$\Omega_{ci}, \rho_i, \lambda_i; \quad \Omega_{ce}, \rho_e, \lambda_e; \quad \lambda_D$$

# Plasma scales (solar wind at 1 AU)

- Larmor radius ($\rho_{i,e}$) and cyclotron frequency ($\Omega_{ci,e}$) of a charged particle (electron or ion=proton) in a magnetic field B:




$$\rho_{i,e} = \frac{V_{\perp i,e}}{\Omega_{ci,e}} \ ; \ \Omega_{ci,e} = 2\pi f_{ci,e} = \frac{eB}{m_{i,e}c}$$
$$\rho_{i=p} \simeq 50\ km; \ f_{ci} \simeq 0.1\ Hz$$
$$\rho_e \simeq 1\ km; \ f_{ce} \simeq 300\ Hz$$

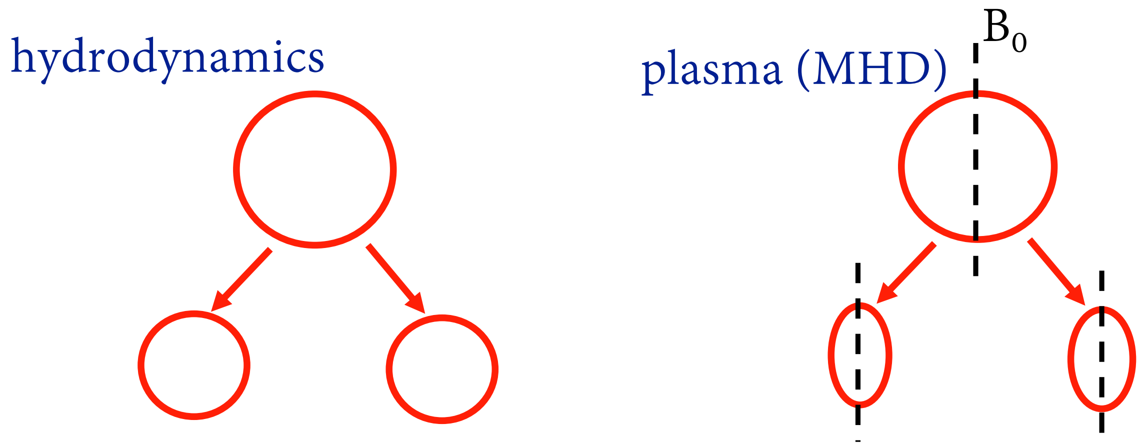
- Inertial length $\lambda_{i,e}$ (demagnetization scale of particles) and plasma frequency ($\omega_p$) :

$$\lambda_{i,e} = \frac{c}{\omega_{pi,e}} \ ; \ \omega^2_{pi,e} = 2\pi f_{pi,e} = \frac{4\pi ne^2}{m_{i,e}}$$
$$\lambda_{i=p} \simeq 40 - 150\ km; \quad f_{pi} \simeq 450\ Hz$$
$$\lambda_e \simeq 1 - 3\ km; \quad f_{pe} \simeq 20\ kHz$$

- Debye length $\lambda_D$ (sphere of influence of a given test charge in a plasma); at L>$\lambda_D$ plasma is quasi-neutral :

$$\lambda_D = \sqrt{\frac{k_B T}{8\pi ne^2}} \simeq 10\ m$$

# Turbulence in space plasmas

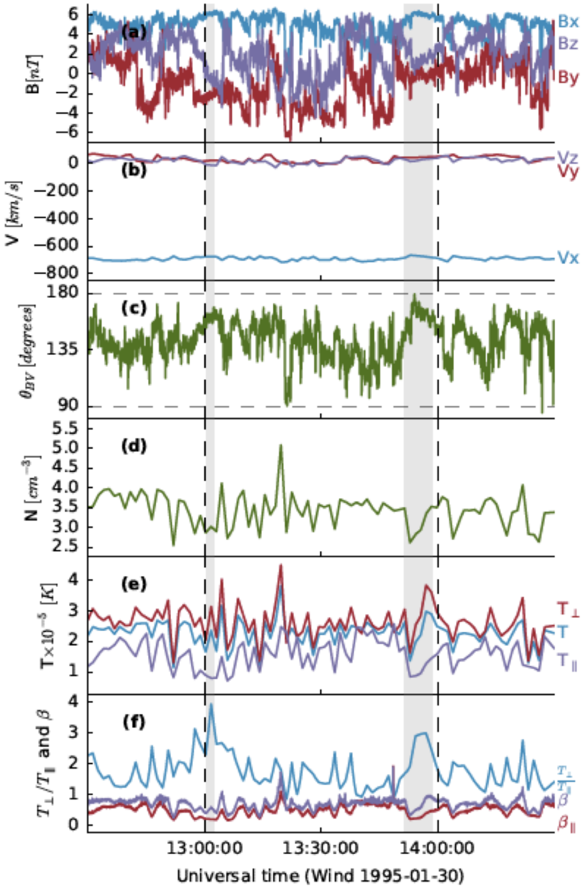



1. Presence of a mean magnetic field $B_0 \Rightarrow$ anisotropy of turbulent fluctuations
2. Plasma waves: Alfven, magnetosonic, mirror, whistlers, kinetic Alfven waves (KAW), etc… (wave turbulence)
3. Nearly no collisions : mean free path ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

- Is there a certain degree of generality in space plasma turbulence ?
- Similarities with HD (spectra & intermittency) ?

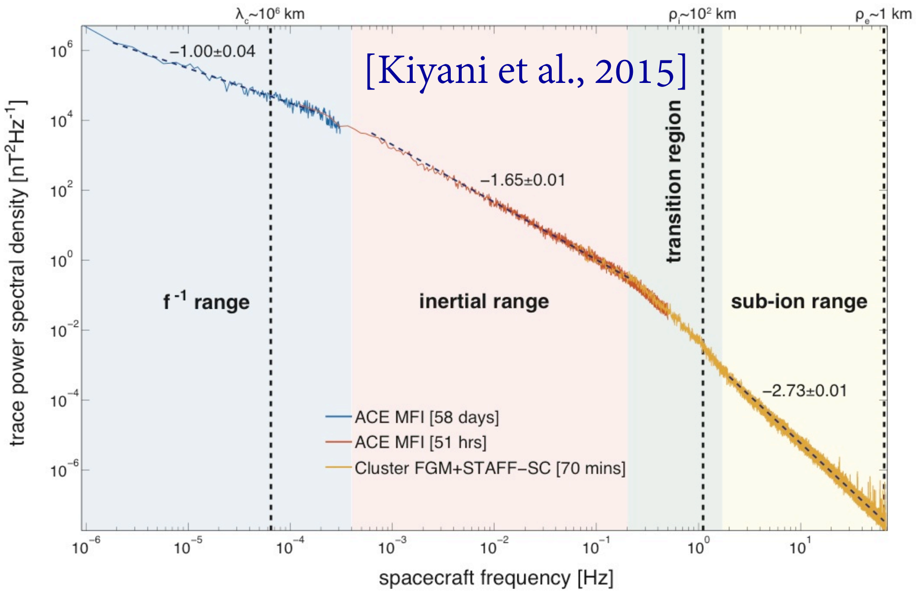
# Magnetic turbulent spectrum in the solar wind

Example of satellite data:




[Lion et al. 2016]

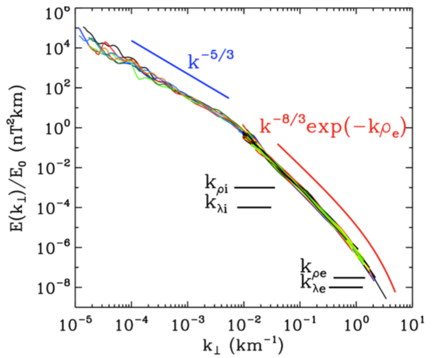
Magnetic fluctuations cover 8 decades in frequencies/scales and ~14 decades in power spectral density:




$$\omega_{obs} = \omega_0 + \mathbf{k} \cdot \mathbf{V}$$

Kolmogorov scaling within the inertial range (5/3= 1.67)

[Alexandrova et al. 2012]

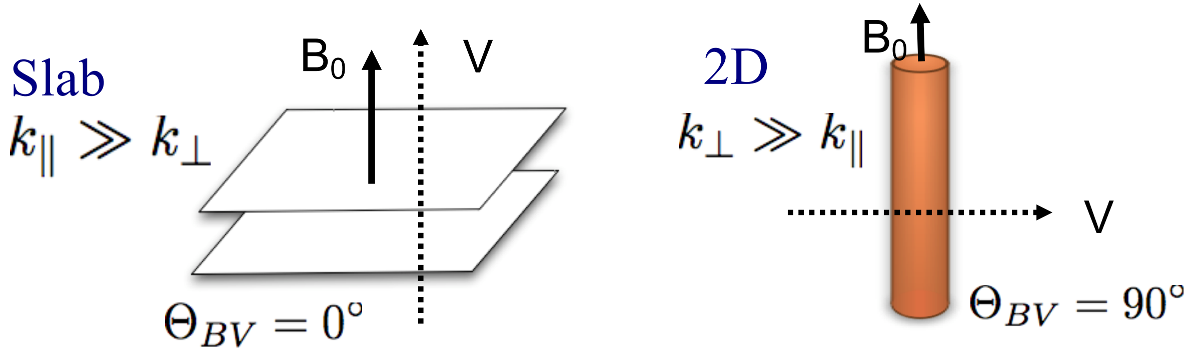


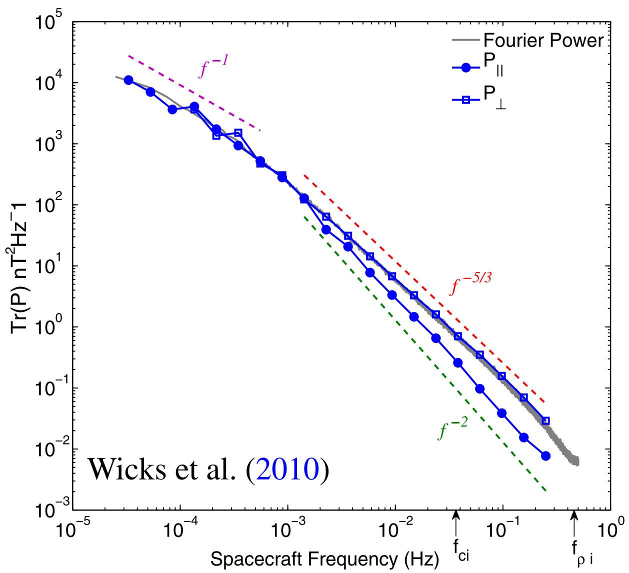

Taylor hypothesis: $\omega_{obs} = \mathbf{k} \cdot \mathbf{V} = kV\cos(\Theta_{kV})$

$\boxed{\omega_{obs} = kV \rightarrow k = 2\pi f/V}$ → $\boxed{f^{-5/3} \sim k^{-5/3}}$

# Magnetic turbulence and wave vector anisotropy

$$\omega_{obs} = \mathbf{k} \cdot \mathbf{V} = kV\cos(\Theta_{kV})$$




'Critical Balance' model [Goldreich and Sridhar, 1995]:

- Incompressible Alfvénic turbulence (δB~δV)
- Balance between linear Alfvén time (along $B_0$) and non-linear time (in plane perp. to $B_0$)

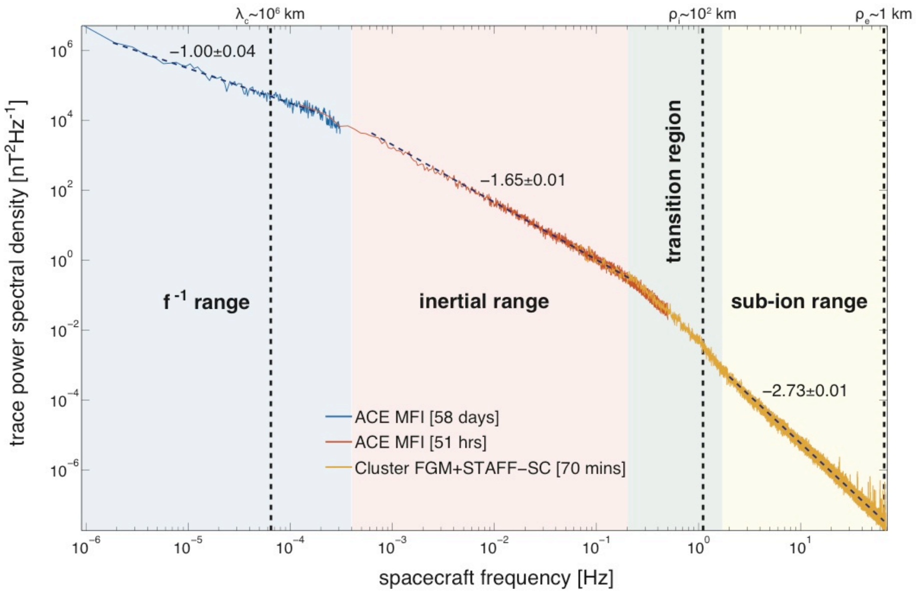
$$\tau_A = \frac{\ell_{\parallel}}{V_A} \sim \tau_{NL} = \frac{\ell_{\perp}}{\delta V_{\perp}}$$

$$\boxed{P(k_{\perp}) \sim k_{\perp}^{-5/3}\ ;\ P(k_{\parallel}) \sim k_{\parallel}^{-2}}$$

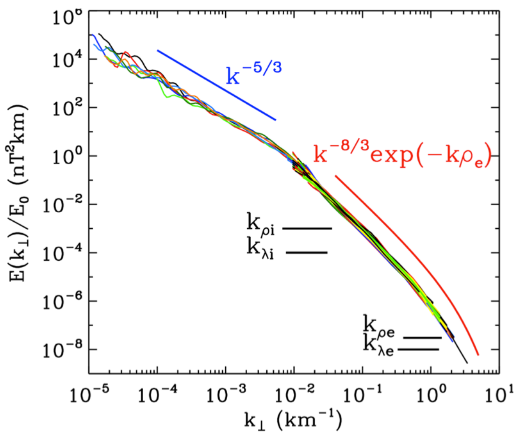
- But, observations show that
  - Velocity spectra do not follow magnetic spectra (expected for Alfven waves)
  - Compressibility…

# Magnetic turbulent spectrum in the solar wind

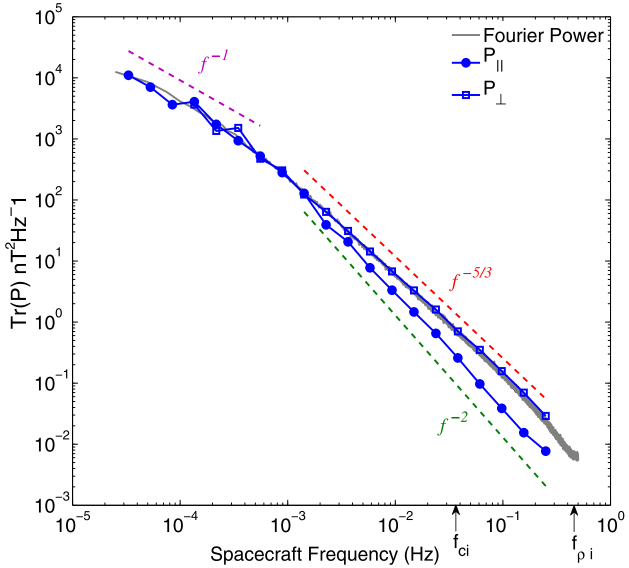
[Kiyani et al., 2015]




[Alexandrova et al. 2012]

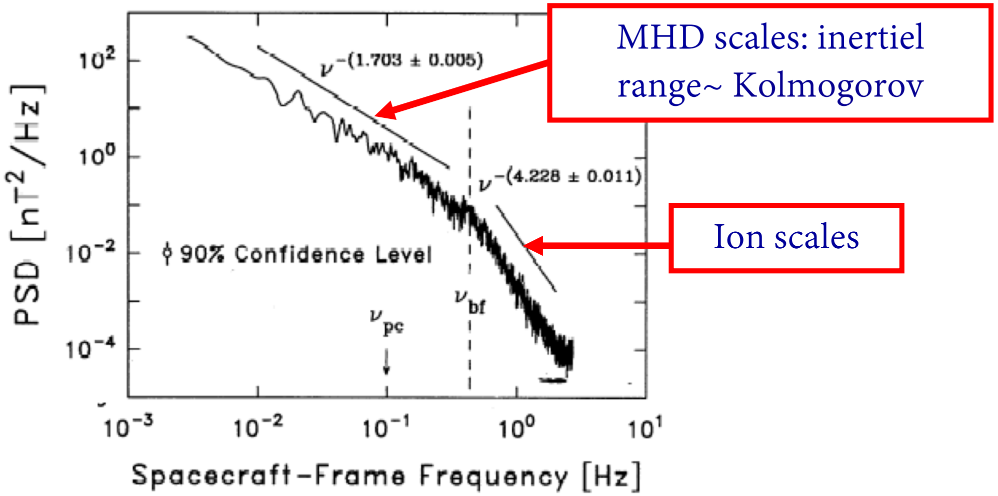


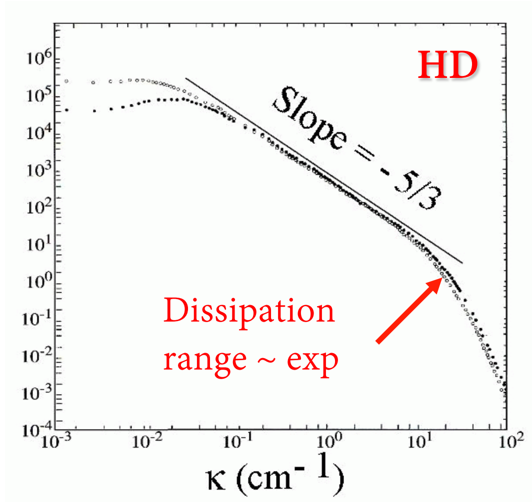

[Wicks et al., 2010]



# Magnetic turbulent spectrum
# Inertial range – ion scales

[Leamon et al,1998] Wind/MAG



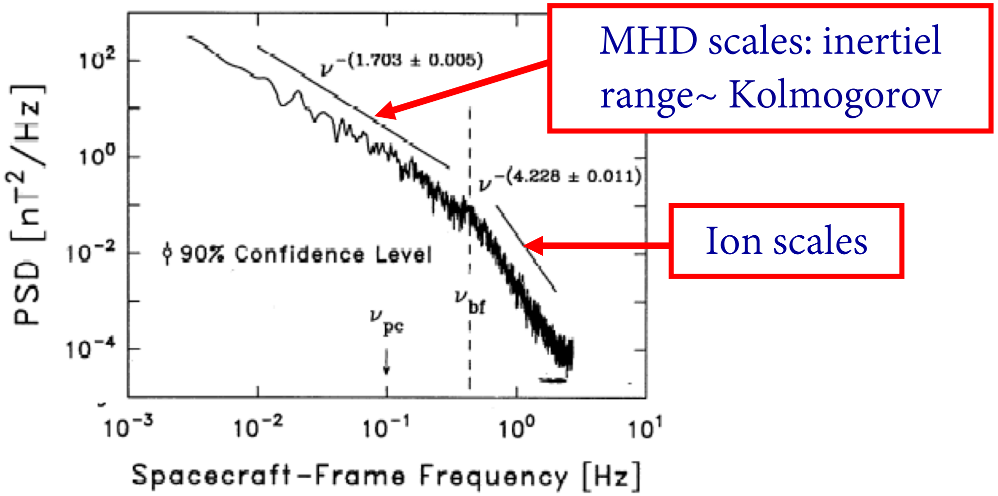




1. MHD scales: $f^{-5/3}$ spectrum
2. There exist a spectral "break" close to ion scales ⇒

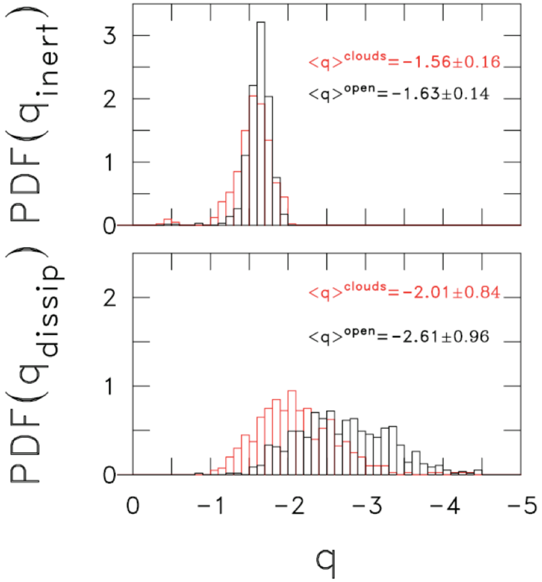
- starting point of a small scale cascade [e.g., Biskamp et al, 1996; Galtier, 2006; Alexandrova et al. 2007, 2008, 2013] or
- onset of dissipation range [e.g., Leamon et al., 1998, 1999, 2000; Smith et al., 2006,…] ?
- If dissipation range ⇒ Why a power law and not an exponential cut-off ?

# Magnetic turbulent spectrum
# Inertial range – ion scales

[Leamon et al,1998] Wind/MAG




[Smith et al., 2006]

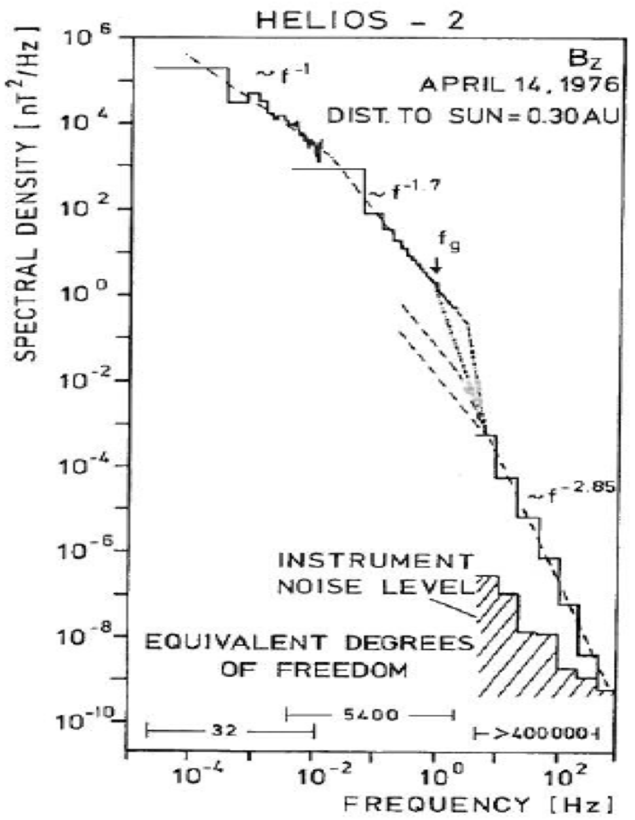


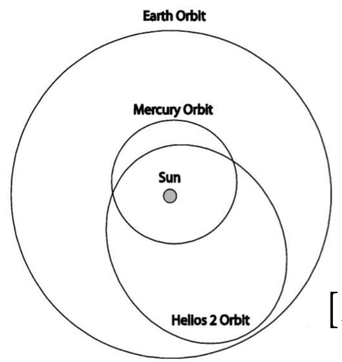

1. Well defined spectrum within the inertial range
2. Spectral index at ion scales is very variable: between -2 and -4 (no general behavior)

- What happens at higher frequencies not resolved by MAG instruments ?

# Helios mission DLR/NASA 1974-1984

[Denskat et al., 1983]



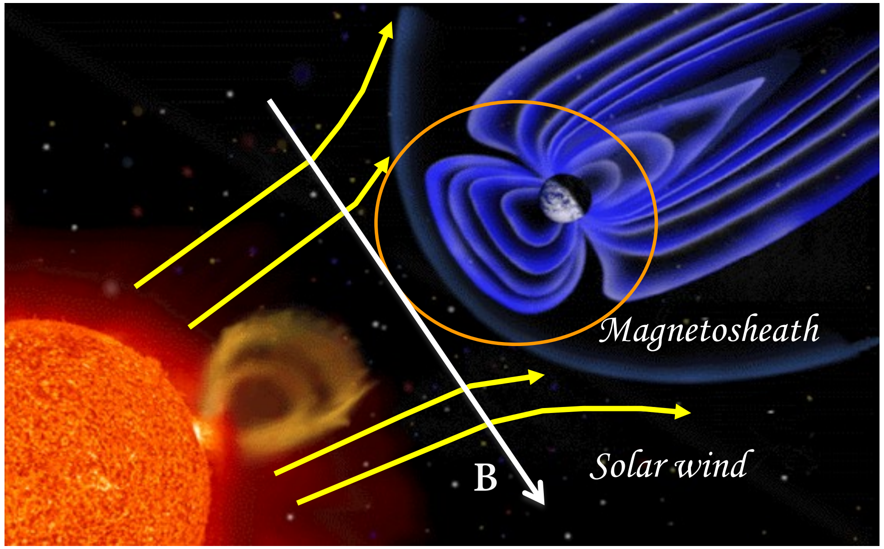



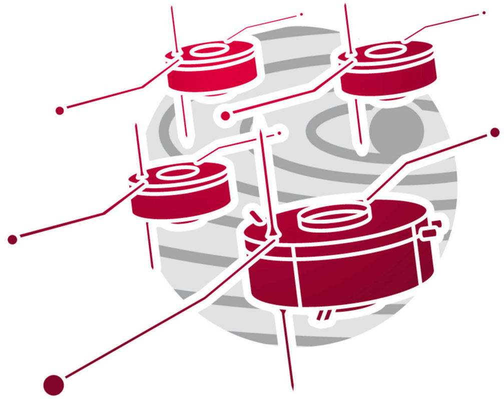

[Burlaga, 2001]

- Radial evolution between 0.3 and 1.0 AU
- Magnetic field measurements with MAG and SCM
- Spectral break around the gap at ion scales (2-4.7 Hz)
- For f > 4.7 Hz (sub-ion scales) and up to 400 Hz,

spectral index of ~3 is observed at 0.3 AU

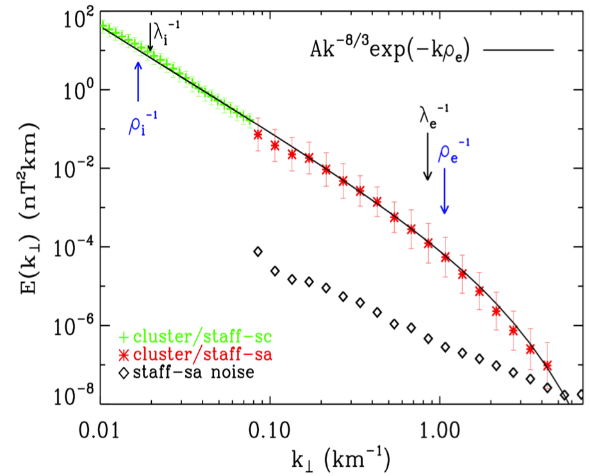
# Cluster mission ESA/NASA, 4 s/c, since 2000



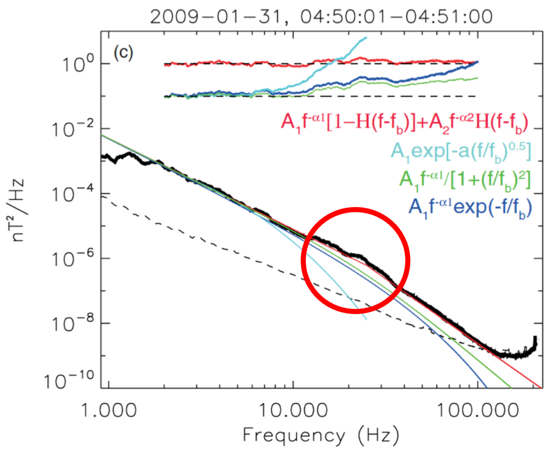



- Multi-satellite mission to study magnetosphere/solar wind connection
- Cluster is in the free solar wind when the field/flow angle is quasi-perpendicular ($Q_{BV} > 65^{o}$)
- Otherwise, Cluster is connected to the bow-shock => shock physics and not solar wind turbulence.
- Thus, with Cluster we can resolve $k_{perp}$ fluctuations
- **STAFF (LPP/LESIA) is the most sensitive instrument by today to measure kinetic plasma scales**

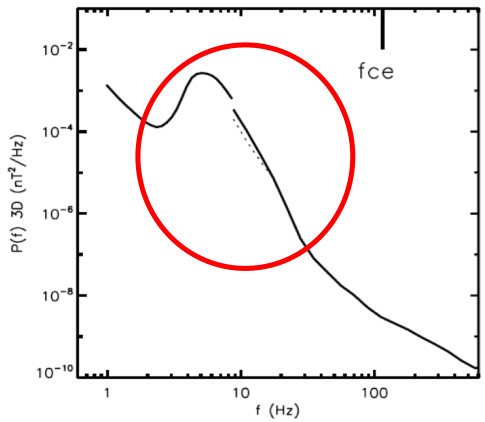
# Magnetic spectra at kinetic scales in the solar wind




[Alexandrova et al. 2009, 2012]



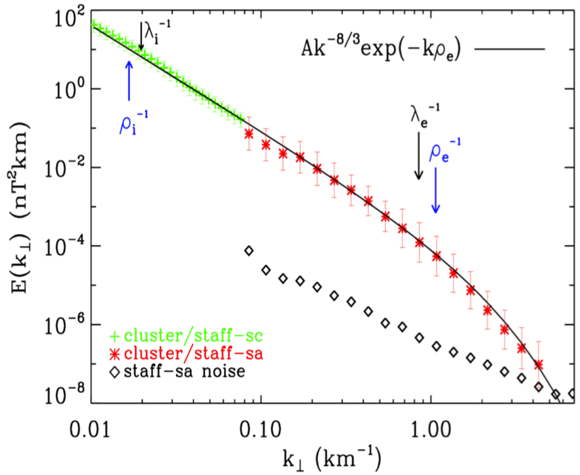

[Sahraoui et al., 2009, 2013]



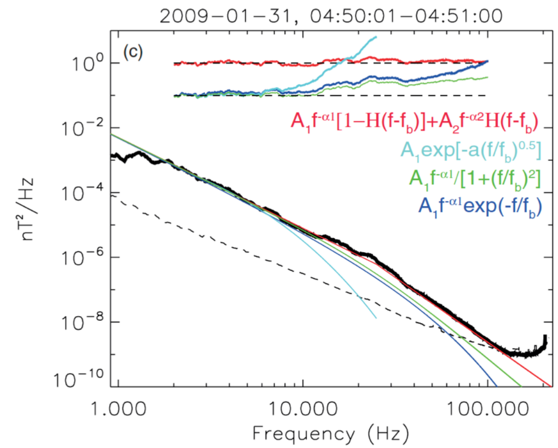

[Lacombe et al. 2014
Jagarlamudi et al., 2020]

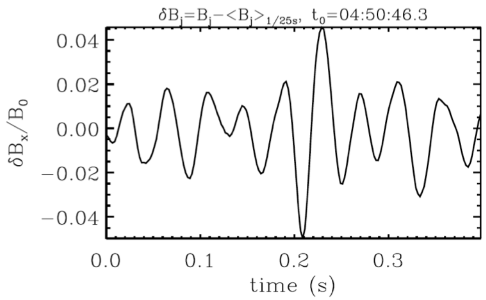
It seems that the spectra are not universal at all…

# Background turbulence vs whistler waves

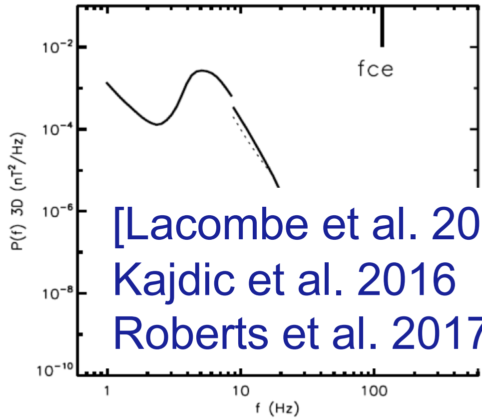



background turbulence with k ⊥ to B and f~0 [Lacombe et al. 2017]

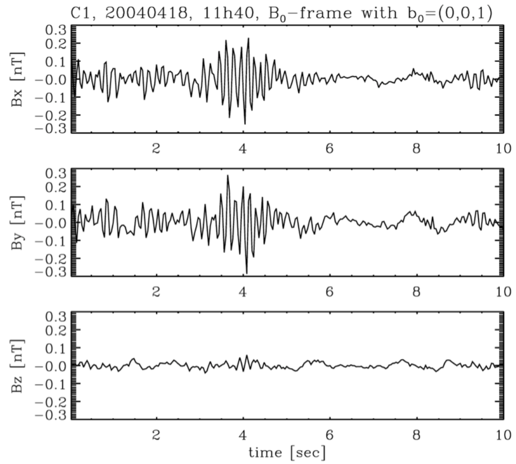



Breaks & Bumps: whistlers with k||B, f ~ (0.1-0.3)$f_{ce}$

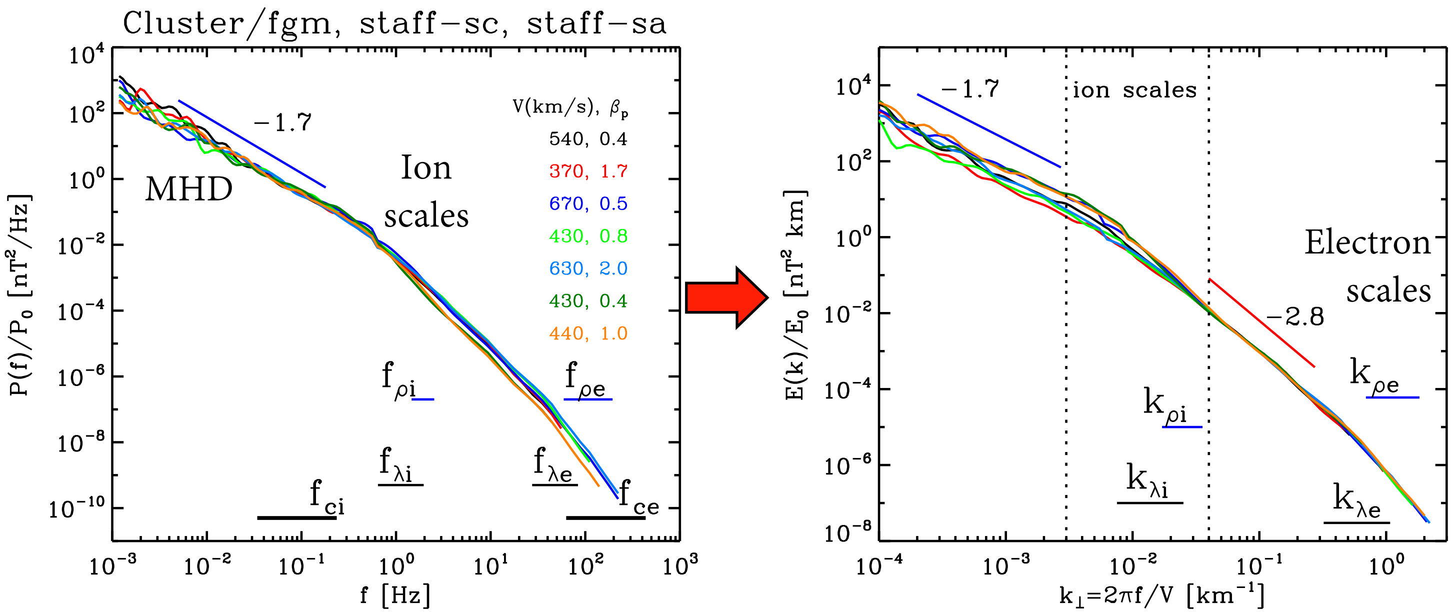



[Lacombe et al. 2014
Kajdic et al. 2016
Roberts et al. 2017]



# Turbulent spectrum from MHD to electron scales

[Alexandrova et al. 2009, PRL; 2013, SSR]




$$\beta_p = \frac{nkT_p}{B^2/8\pi}$$

$$f_{\rho_e} = V/2\pi\rho_e$$

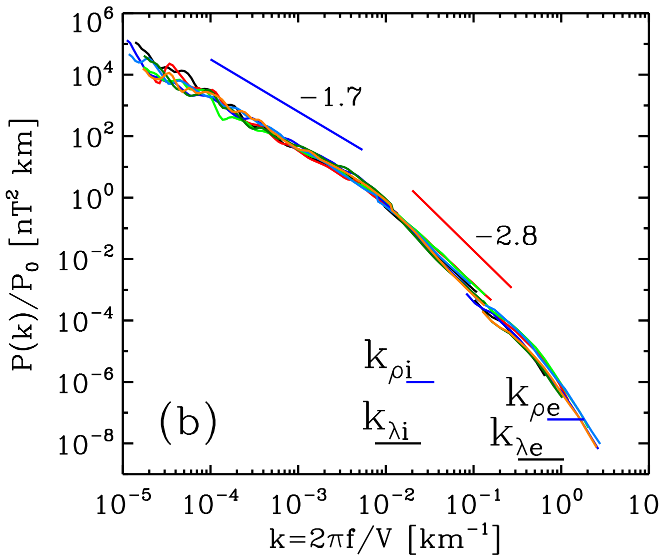
$$\rho_e = \frac{V_{th,e}}{2\pi f_{ce}}$$

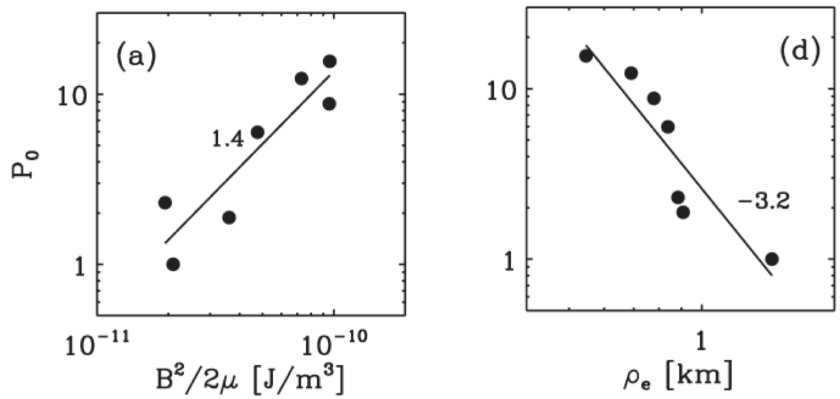
$$k_{\rho_e} = 1/\rho_e$$

- Superposition of different spectra at sub-ion scales seems to indicate general behaviour : spectrum ~$k_{perp}^{-2.8}$
- End of the cascade ? Dissipation scales ?

# Dissipation scale?

[Alexandrova et al. 2009, PRL] Cluster/FGM+STAFF data




?

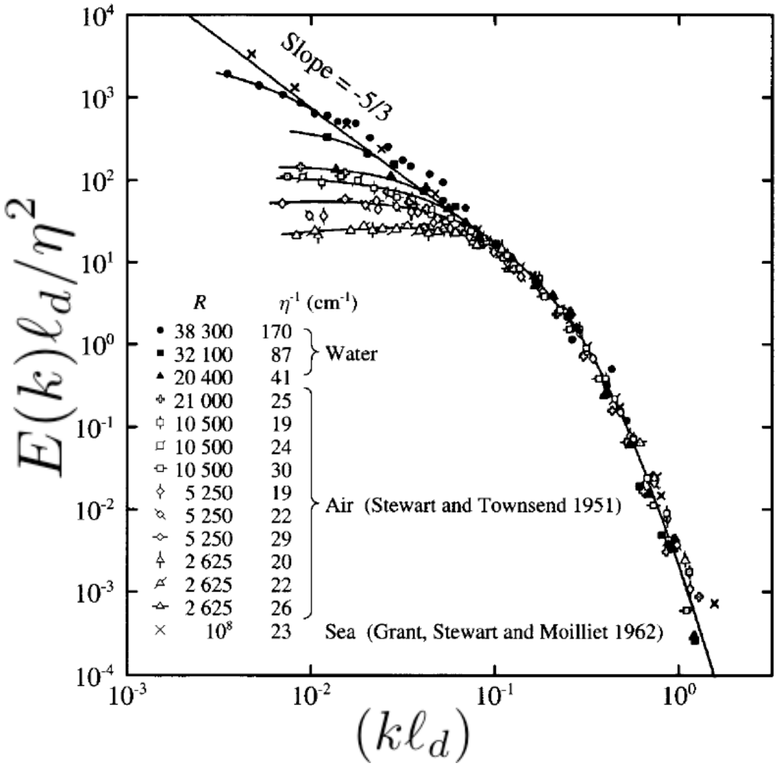
$$\boxed{\ell_d \sim \rho_e}$$

Quasi-stationary turbulence

- energy transfer rate $\varepsilon$ = energy dissipation rate $\varepsilon_d$
- $\varepsilon = \eta^3\, l_d^{-4}$, where $l_d$ is dissipation scale, $\eta$ is viscosity
- amplitude of the spectrum $P_0 \sim \varepsilon^{2/3} \sim l_d^{-8/3}$

# Universal Kolmogorov's function

[Frisch, Turbulence: the legacy of Kolmogorov, 1995]




$$E(k)\ell_d/\eta^2 = F(k\ell_d)$$

$\ell_d$: dissipation scale

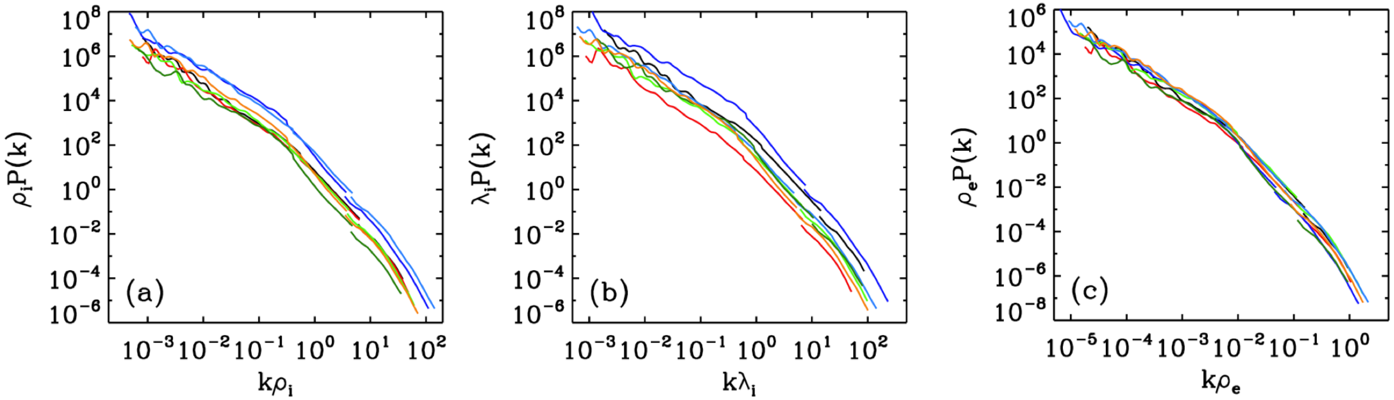
$\eta$: viscosity

In HD turbulence, this normalization collapses spectra measured under different conditions.

# Dissipation scale?

Universal Kolmogorov's function: $\boxed{E(k)\ell_d/\eta^2 = F(k\ell_d)}$

Let us try to apply this kind of normalization for solar wind spectra and for different candidates for the dissipation scale: $\ell_d = \rho_{i,e}, \lambda_{i,e}$



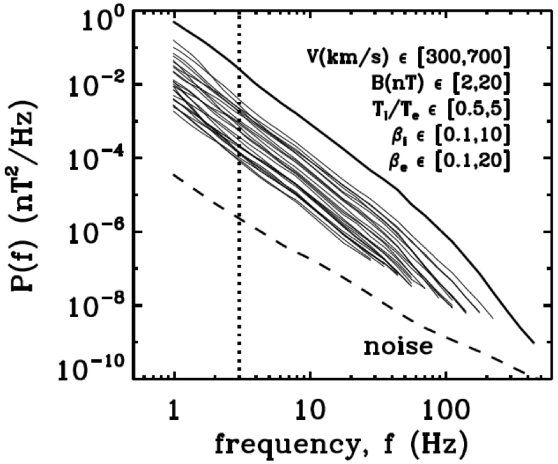

- Assumption: $\eta$=Const
- $\kappa\rho_i$ & $\kappa\lambda_i$ - normalizations are not efficient for collapse
- $\kappa\rho_e$ normalization bring the spectra close to each other

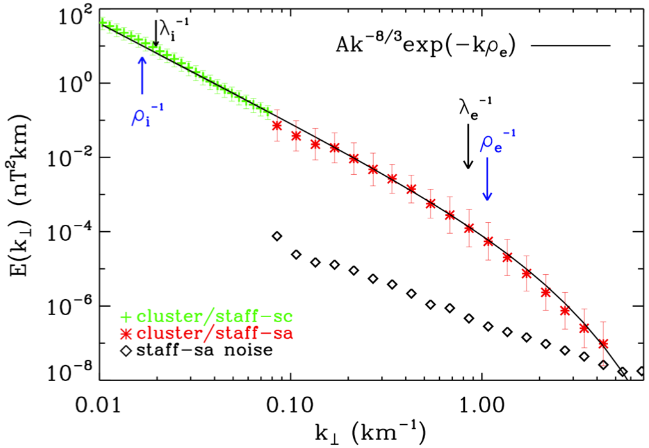
$\Rightarrow$ $\boxed{\ell_d \sim \rho_e}$

[Alexandrova et al., 2009, PRL]

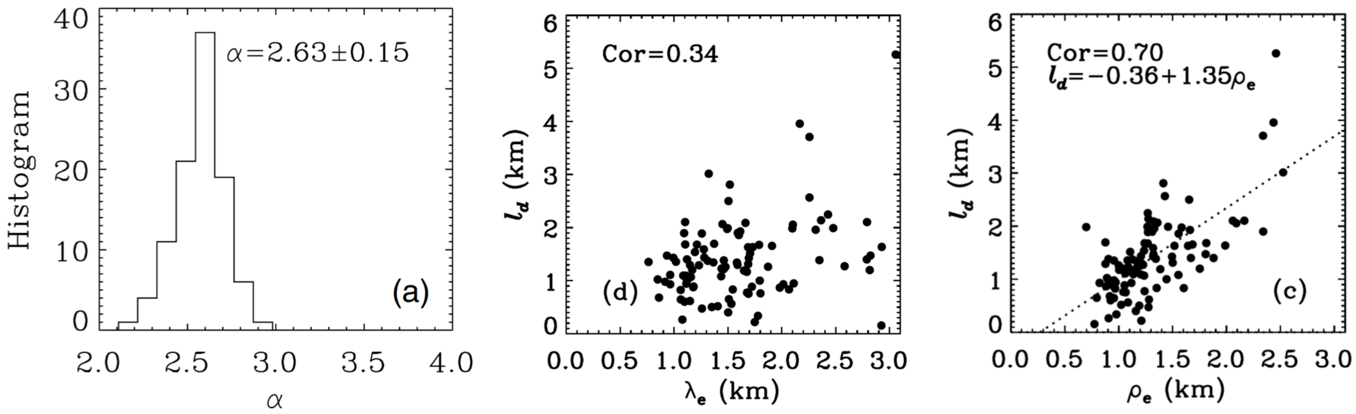
# Larger statistical study with Cluster/STAFF

[Alexandrova et al., 2012, APJ]



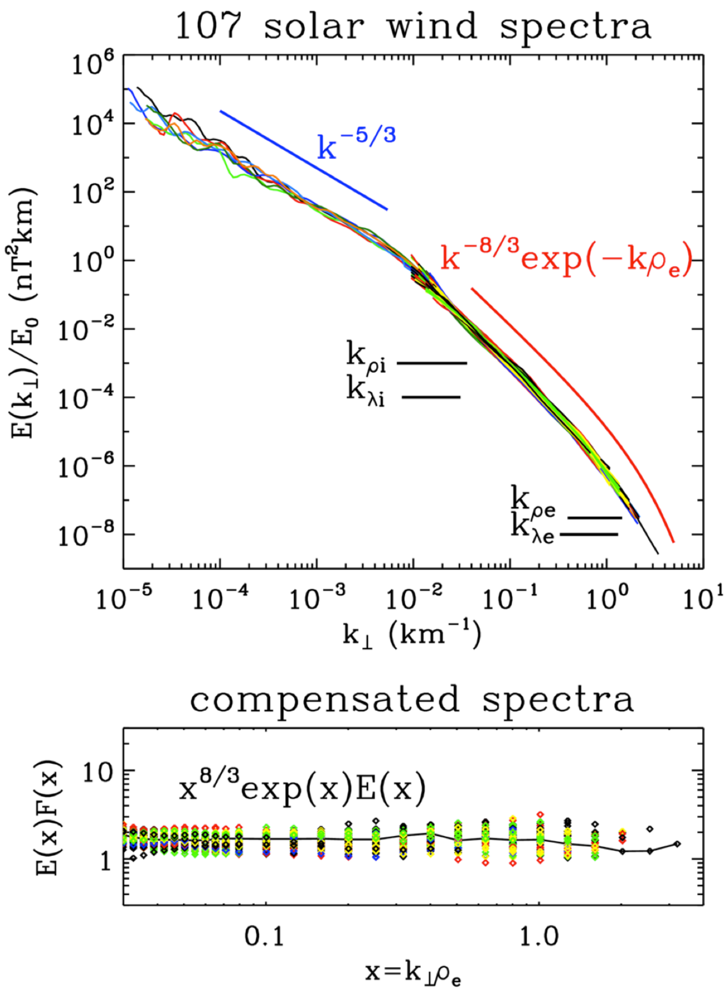




[Chen, et al., 1993, PRL] dissipation range spectrum in fluids: $E(k) = Ak^{-\alpha}\exp\left(-k\ell_d\right)$




$\boxed{\ell_d \sim \rho_e}$

# General spectrum at kinetic scales



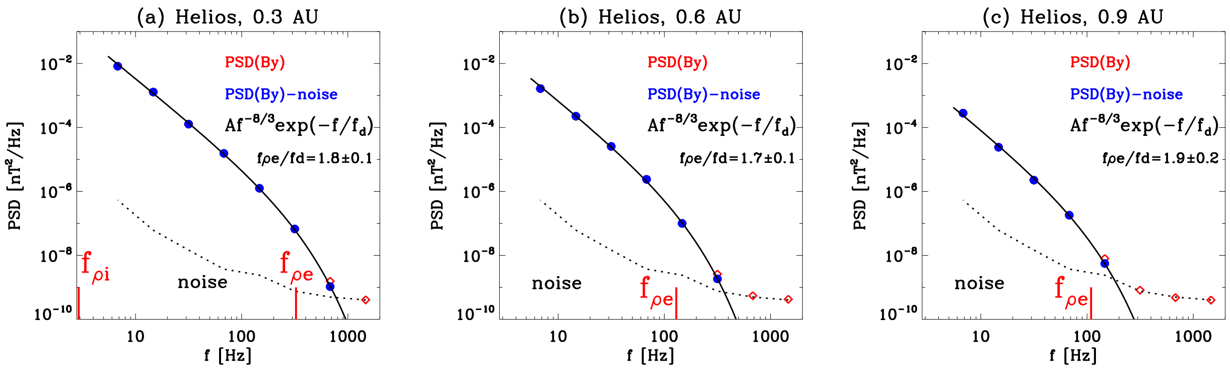

- For different solar wind conditions we find a general spectrum with "fluid-like" roll-off spectrum at electron scales

- Electron Larmor radius seems to play a role of the dissipation scale in collisionless solar wind [Alexandrova et al., 2009 PRL, 2012 APJ]

$$\boxed{E(k) = Ak^{-8/3}\exp(-k\rho_e)}$$

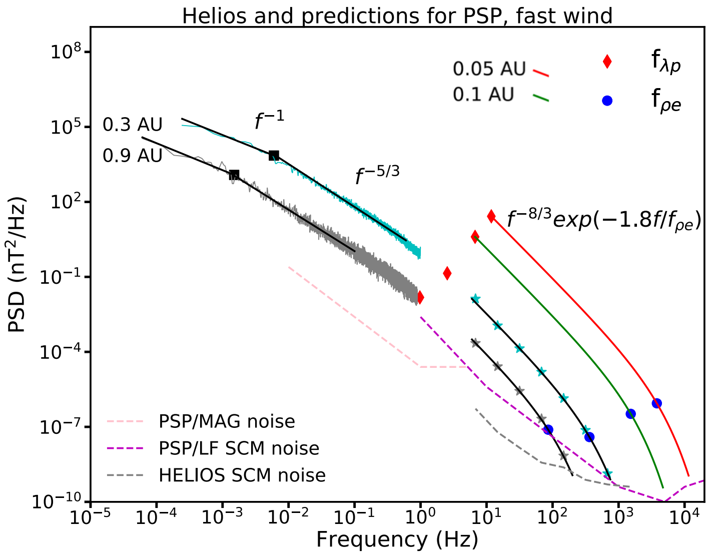
- Recently, we find similar spectrum closer to the Sun at 0.3 AU, indicating universality of the phenomenon [Alexandrova et al. 2020, under revision]

# Kinetic spectra closer to the Sun




[Alexandrova, Jagarlamudi et al. 2020, under review]

$$\boxed{f_{\rho_e} = \frac{V}{2\pi\rho_e}}$$

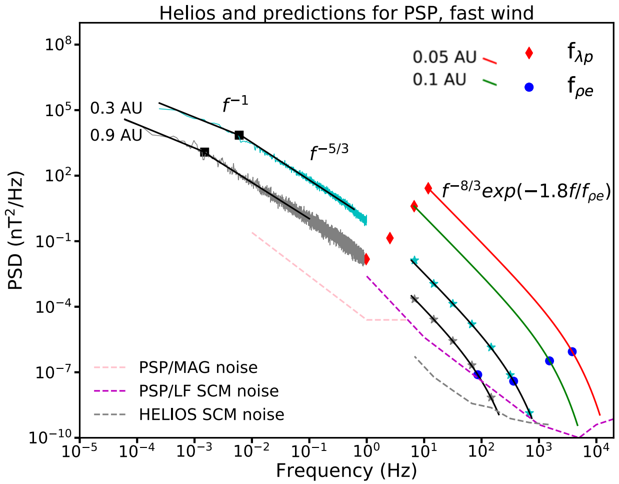


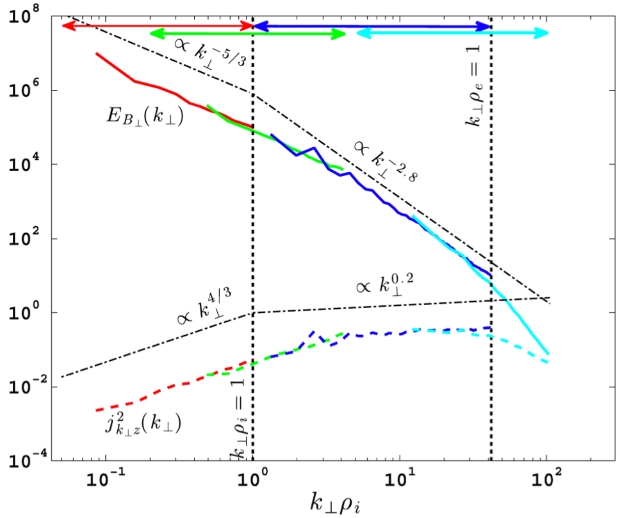

- We expect that the spectral properties we observe are generic for space plasmas turbulence at sub-ion to electron scales.
- First part of kinetic spectrum (up to ~100 Hz) has been already observed by PSP at 0.17 AU [Bale et al., 2019, Bowen et al. 2020].

NB: PSP/SCM noise is the same as the one at Solar Orbiter/SCM…

**What is 'behind' this spectrum?**

# Physics of the solar wind turbulent cascade




[TenBarge et al. 2013, APJ]

- **Inertial range**: Alfven waves propagating from the Sun, Critically Balanced turbulence ($\tau_A = \tau_{NL}$)

- **Ion transition**: Alfven waves become Kinetic Alfven Waves (KAWs), e.g., Schekochihin et al., 2009, Howes et al. 2006, 2008, 2011, Salem et al. 2012, …

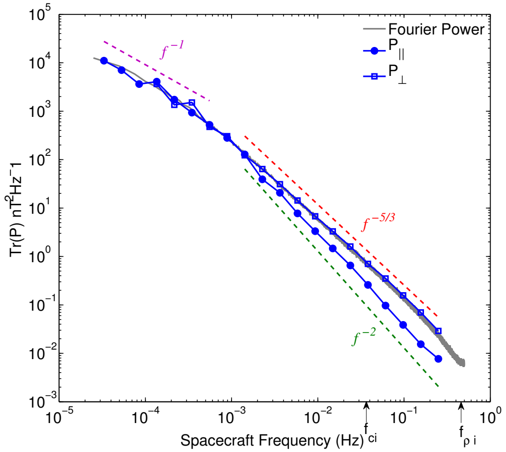
- **Sub-ion scales**: Critically Balanced KAW turbulence ($\tau_{KAW} \sim \tau_{NL}$), e.g., Boldyrev and Perez 2012, TenBarge et al. 2013, Howes et al.,…

- **Dissipation**: Landau damping of KAWs, e.g., Howes et al. 2011, TenBarge et al. 2013, Passot & Salem 2015, Schreiner & Saur, 2017

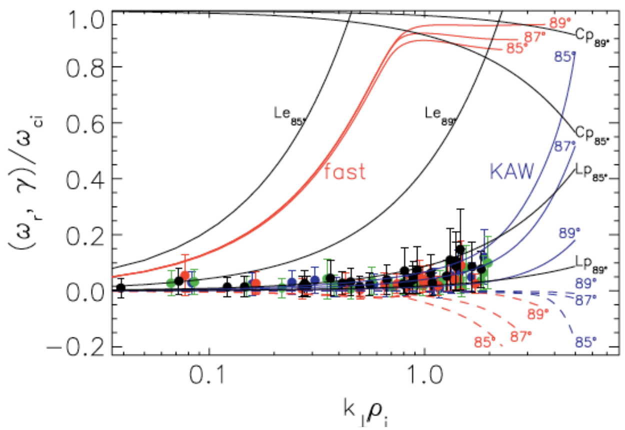
# Solar wind turbulence : widely accepted picture

- Inertial range: Alfven waves propagating from the Sun, Critically Balanced turbulence ($\tau_A = \tau_{NL}$)
- Ion transition: Alfven waves become Kinetic Alfven Waves (KAWs), e.g., Schekochihin et al., 09
- Sub-ion scales: Critically Balanced KAW turbulence ($\tau_{KAW} \sim \tau_{NL}$), e.g., Boldyrev and Perez 12
- Dissipation: Landau damping of KAWs, e.g., Howes et al. 11, TenBarge et al. 2013, Passot & Salem 15, Schreiner & Saur, 17

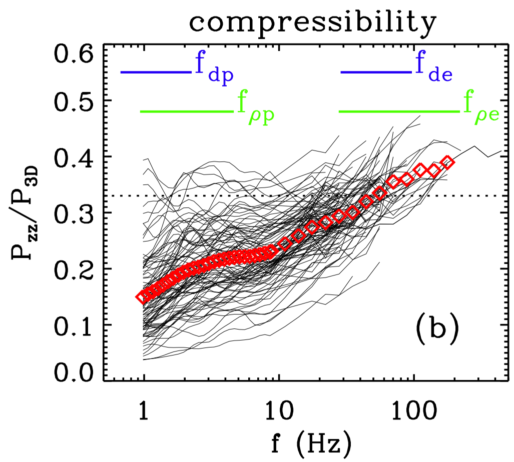
## This picture is based on mean properties of turbulent flows, e.g.,:




Spectra are in agreement with Critical Balance



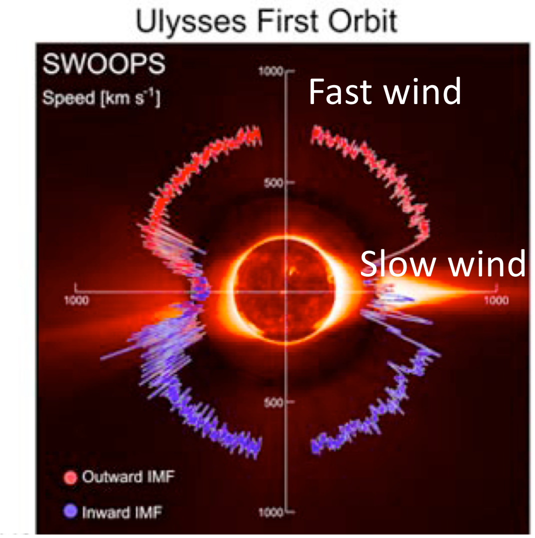

Linear dispersion of KAWs describes the data [Sahraoui et al. 10, Roberts et al., 13]



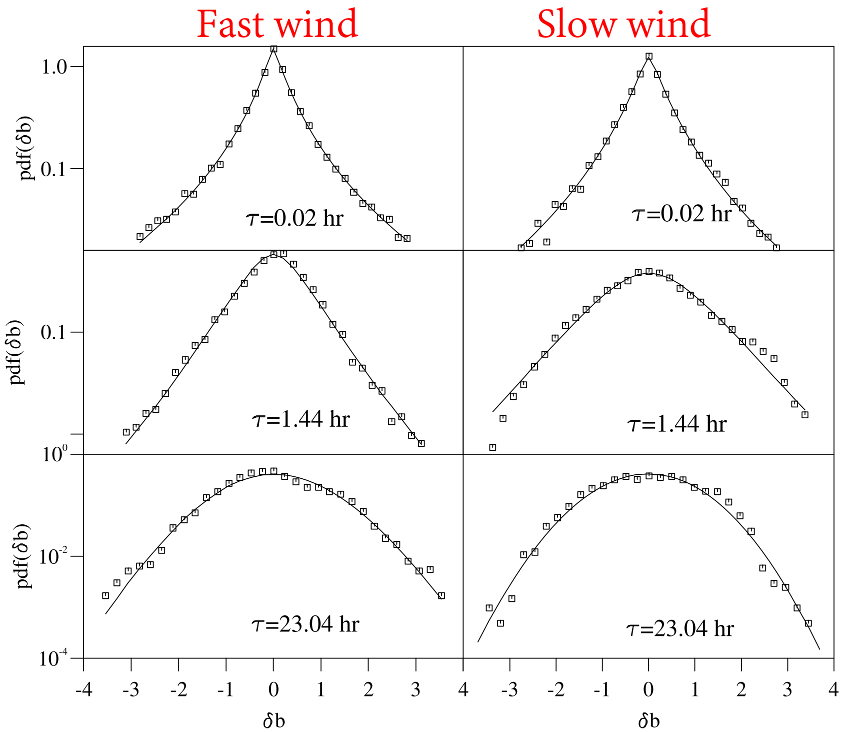

Compressibility in agreement with KAWs [Lacombe et al. 17, Groselji et al. 19, Matteini et al. 20]

## Intermittency in all this ?

# II. Intermittency in space plasma turbulence



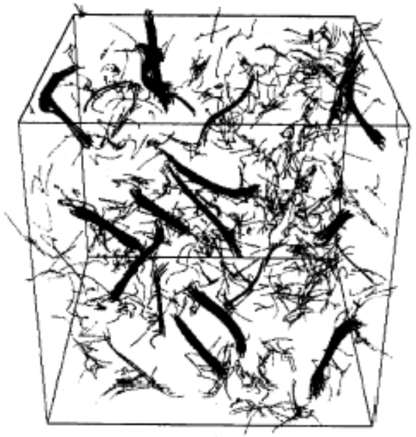

[Sorriso-Valvo et al. 1999]




$$\left|\Delta\mathbf{b}\right| = \left|\mathbf{b}(s+\Delta s) - \mathbf{b}(s)\right|$$

# Definition of coherent structure

[She et al., 1991]



1. Farge & Schneider (2015): 'Everything that is not noise'

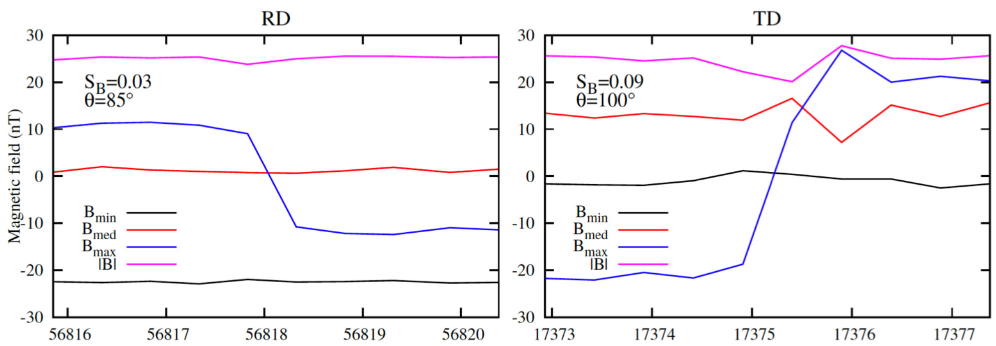
2. Inspired by Fiedler (1988) & Lesieur (1993)

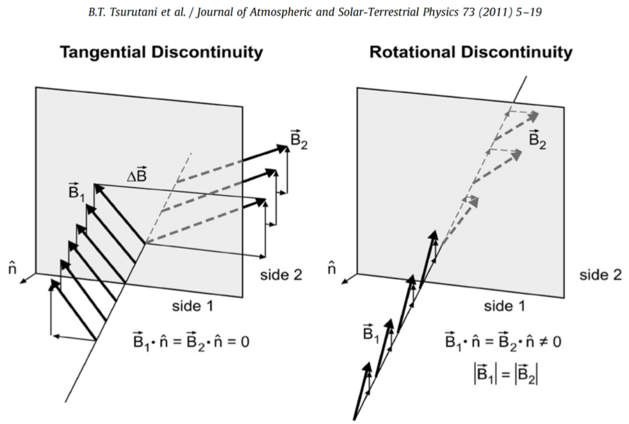
- High amplitude event localized in space
- Delocalisation in Fourier space
- Phase coupling over a large range of scales
- Particular topology
- Life time $\gg$ life time of random fluctuations at the smallest scale of the structure

# Looking for signatures of coherent structures

Increments of magnetic field and Partial Variance of Increments (PVI) Method

$$\mathrm{PVI}(t,\tau) = \frac{|\Delta \boldsymbol{B}(t,\tau)|}{\sqrt{\langle|\Delta \boldsymbol{B}(t,\tau)|^2\rangle}}$$



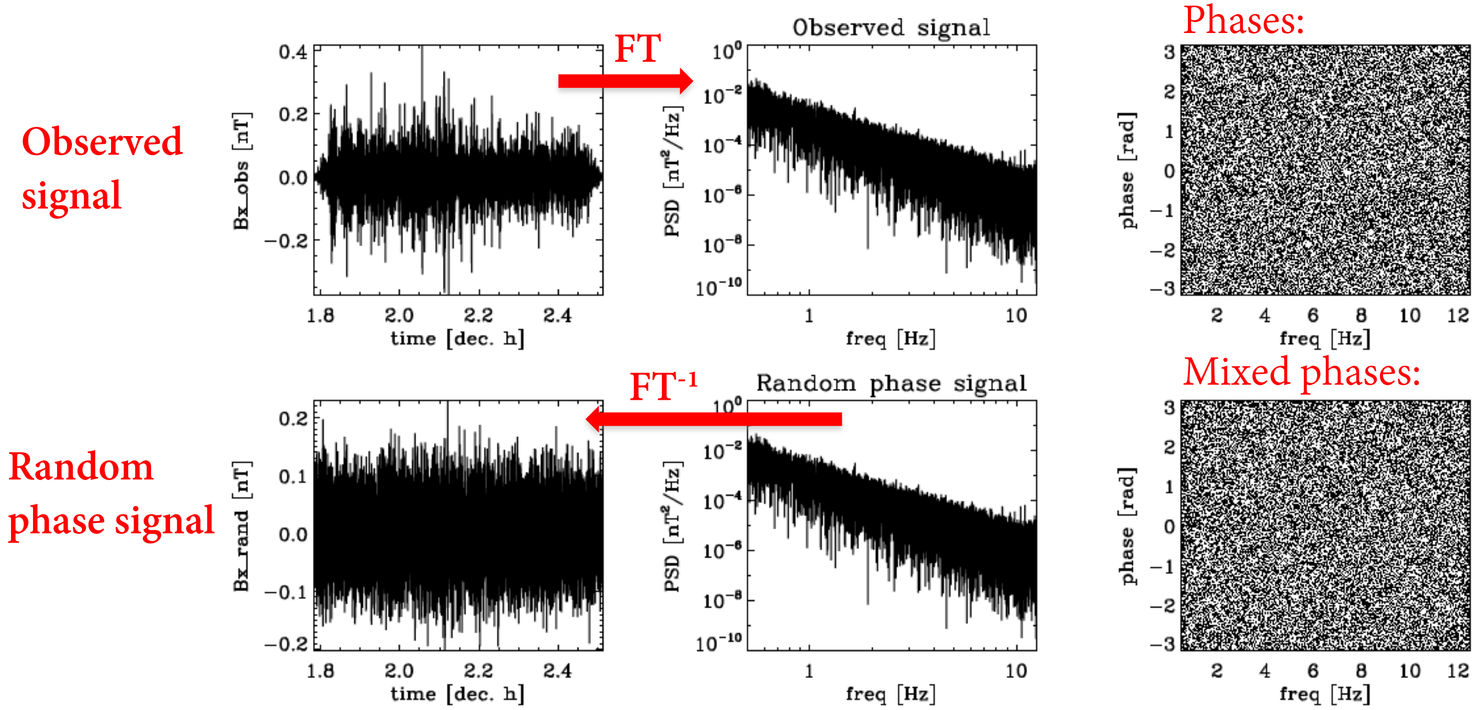




[e.g., Veltri & Mangeney 1999, Servidio, et al. 2008, Greco, et al. 2009, 2012, 2014, Perri et al. 2012]

- Are there other types of structures?

# Non-Gaussianity: what does it mean?

Cluster-1/STAFF-SC measurements, 2002-02-19




From the observed signal we construct a signal with random phases but with the same spectrum.

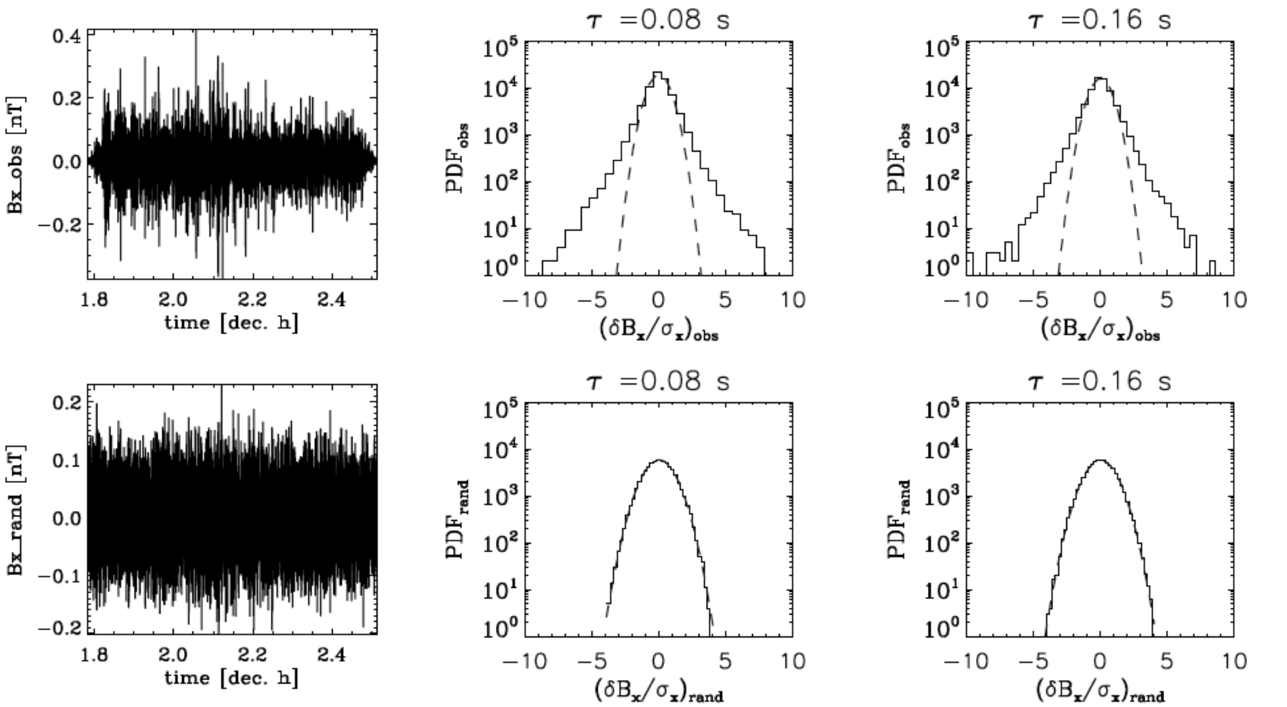
[Rossi, Tesi di Lauria, 2011; Hada et al. 2003; Koga & Hada, 2003; Sahraoui, 2008, Einaudi & Velli 1999]

# Non-Gaussianity: what does it mean?

[Claudia Rossi, Tesi di Laurea, 2011]

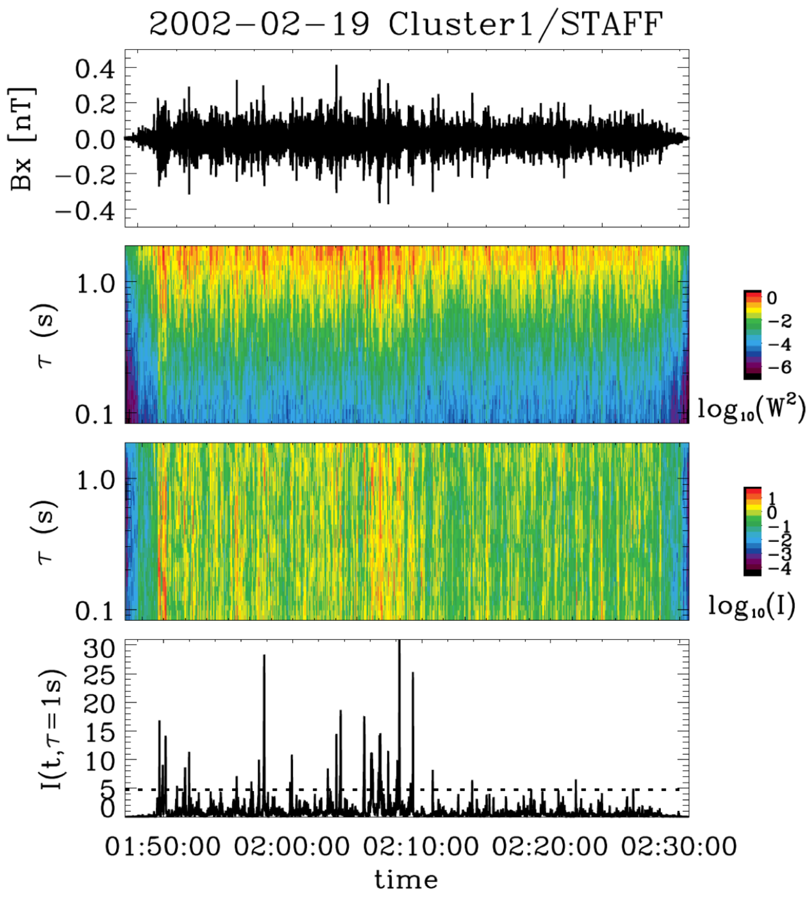
Observed signal

Random phase signal




Non-Gaussian tails ⇔ coupled phases !

# Wavelet transform and Local Intermittency Measure




Morlet Wavelet Transform

$$W(t,\tau) = \sum_{j=0}^{N-1} B_x(t_j)\psi_0^*[(t_j - t)/\tau]$$

$$\psi_0(t) = \pi^{-1/4} e^{-i\omega_0 t} e^{-t^2/2}$$

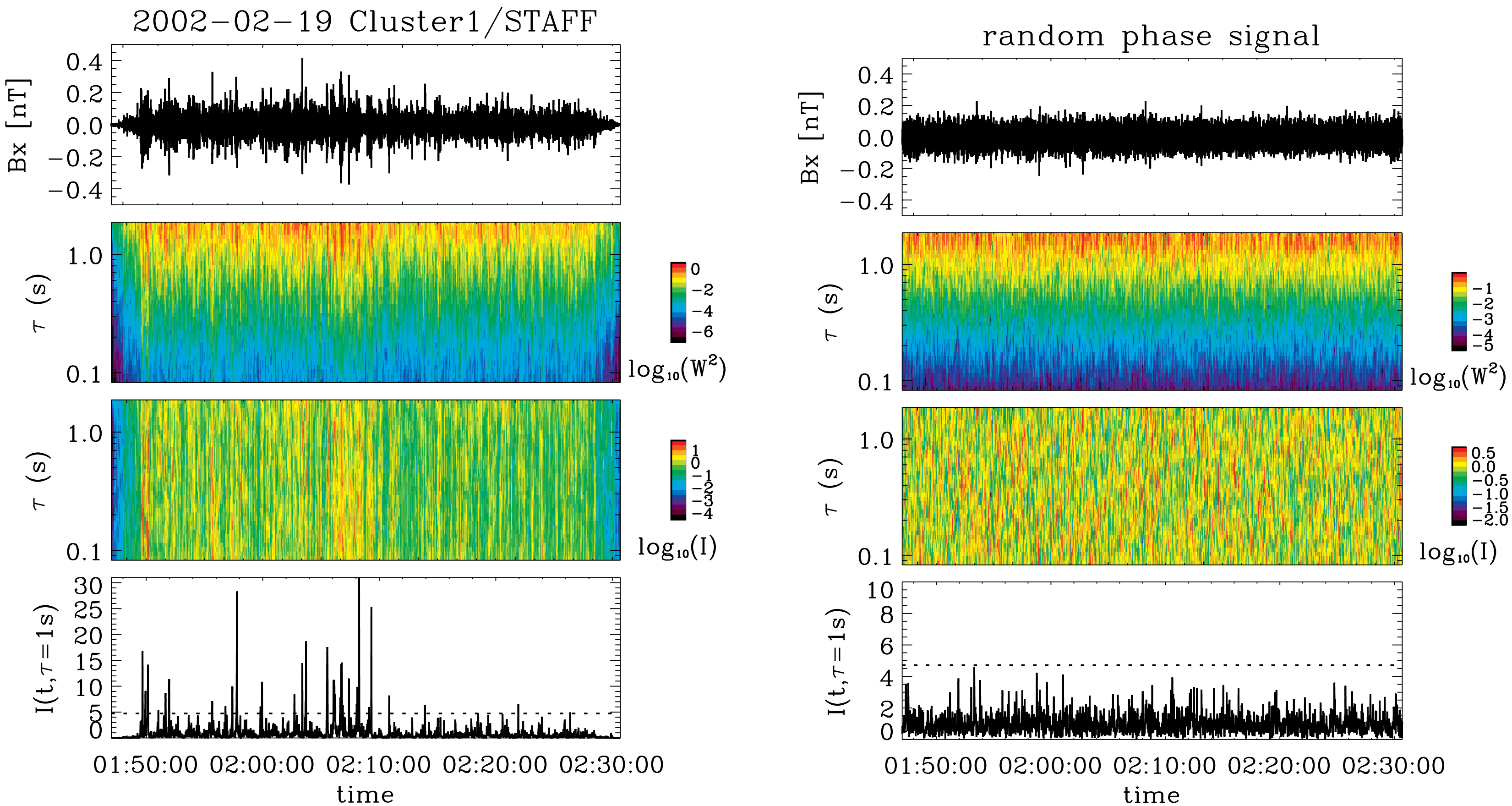
Local Intermittency Measure (LIM)

$$I(t,\tau) = \frac{|W(t,\tau)|^2}{\langle |W(t,\tau)|^2 \rangle_t}$$ [Farge 1992]

We observe

- stalactite-like events in wavelet scalogram $W^2(t,\tau)$, see $2^{nd}$ panel
- Vertical lines in LIM, see $3^{rd}$ panel

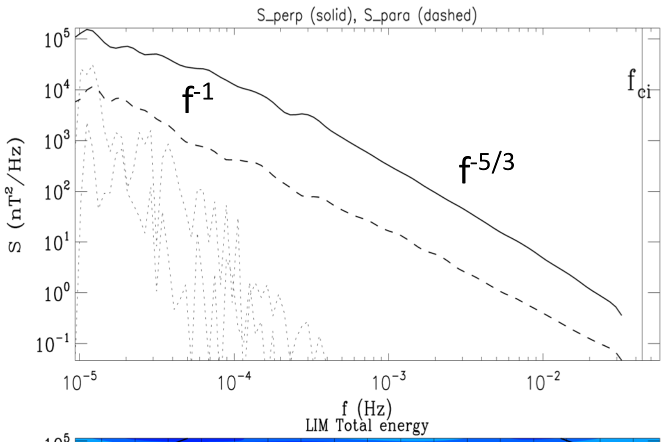
# Observed signal vs random phase signal

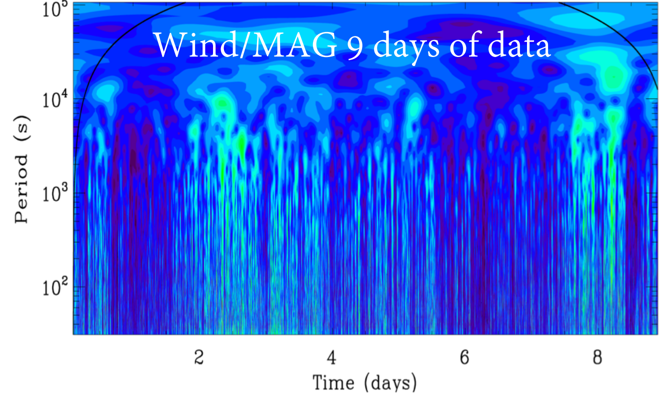



- LIM of $B_{x,rand}$: homogeneous energy distribution of the signal in time-scale plane
- Thus, vertical lines in LIM of $B_{x,obs}$ correspond to events with coupled phases $\Rightarrow$ coherent structures?

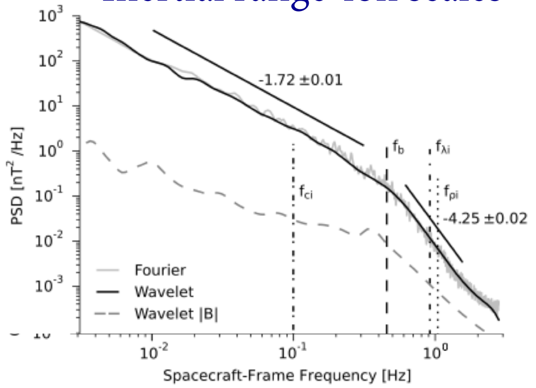
# Signatures of coherent structures from MHD to electron scales

### Energy injection scales – inertial range

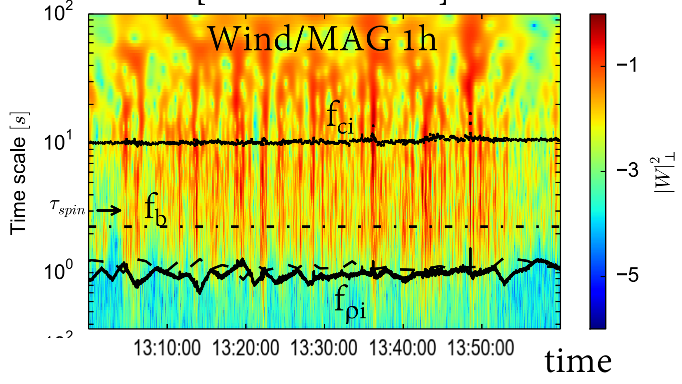


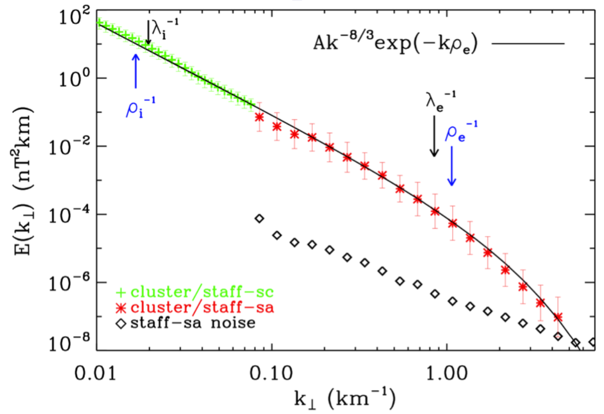

### Inertial range-ion scales

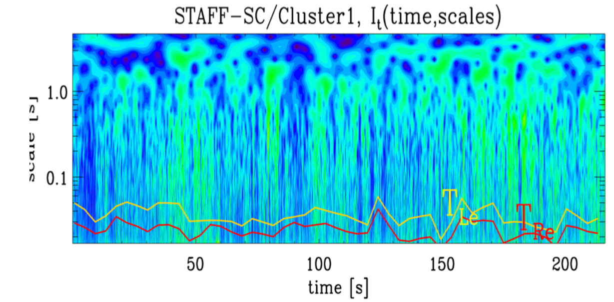



[Lion et al. 2016]




### Kinetic plasma scales



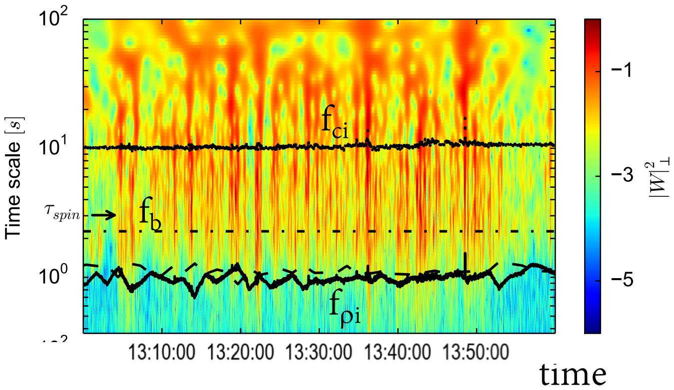




[Inna Orel, Master Thesis 2017]
~3 min of Cluster/STAFF data

- Vertical lines in LIM : signatures of coherent structures
- They are visible from the onset of the inertial range at ~$3\cdot10^3$ s

and up to the smallest resolved scales around electron Larmor radius $\rho_e$

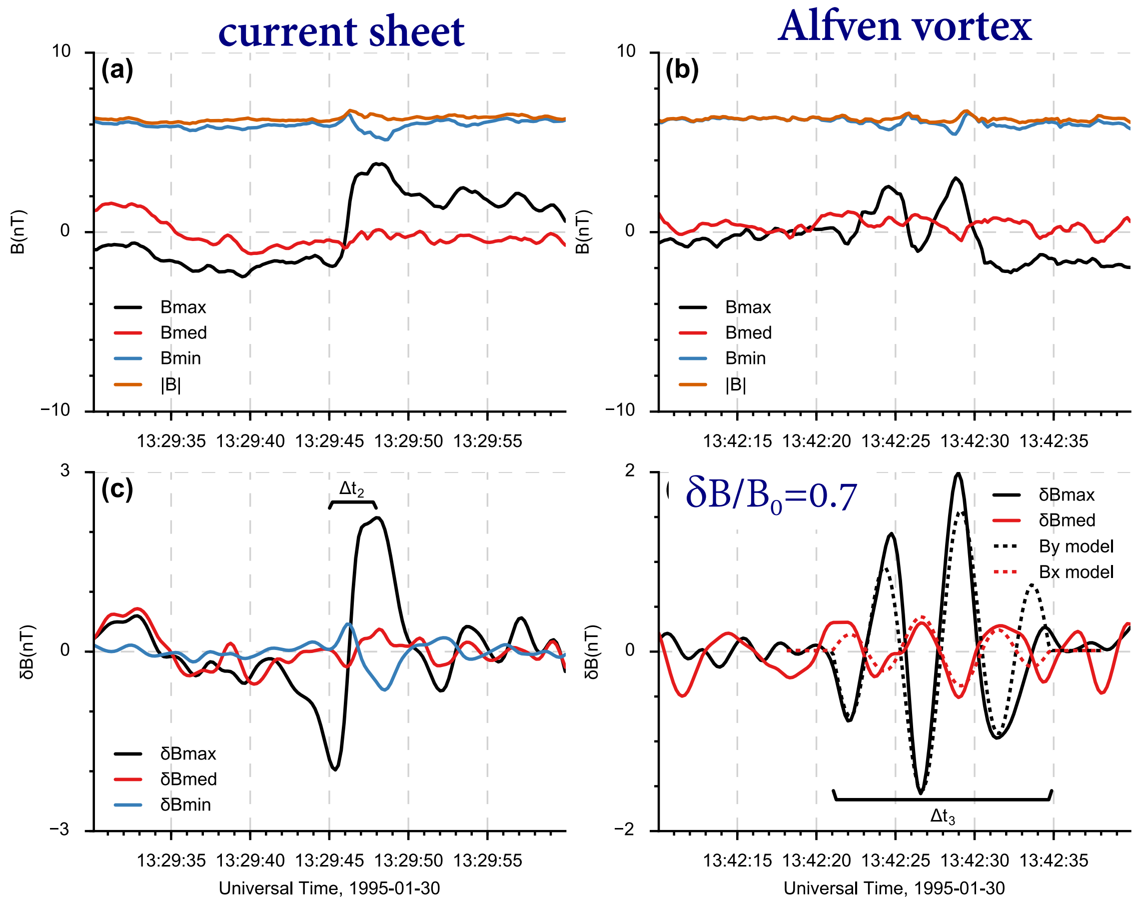
# Coherent structures within the inertial range




At the times of events,
in physical space we see

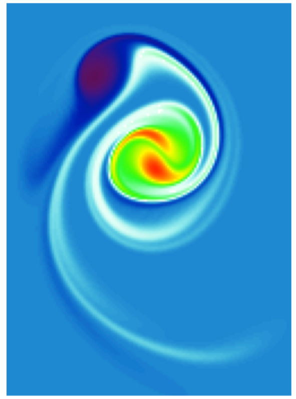
- **current sheets**
- **Alfven vortices**

(oblique $\Theta_{BV}$)




[Lion, Alexandrova & Zaslavskiy, 2016, APJ]

# Alfven vortices ~ 2D incompressible HD vortices

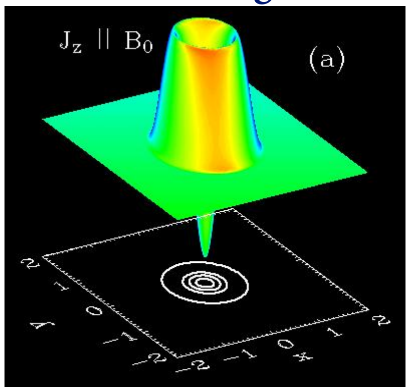


Vector potential, A, ~ to stream function ⇒ field lines || stream lines &
current || vorticity [Petviashvilli & Pokhotelov, 1992]

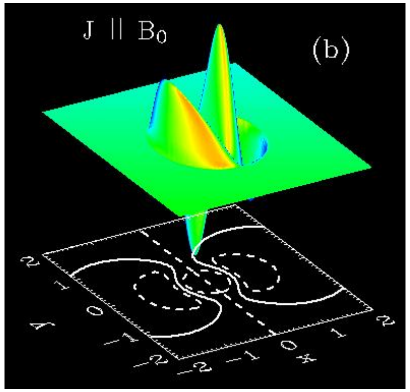
$$\frac{\partial_z}{\nabla_\perp} \sim \frac{\partial_t}{V_A \nabla_\perp} \sim \frac{\delta B_z}{\delta B_\perp} \sim \frac{\delta V_z}{\delta V_\perp} \sim \frac{\delta B_\perp}{B_0} \sim \frac{\delta V_\perp}{V_A} \sim \varepsilon.$$

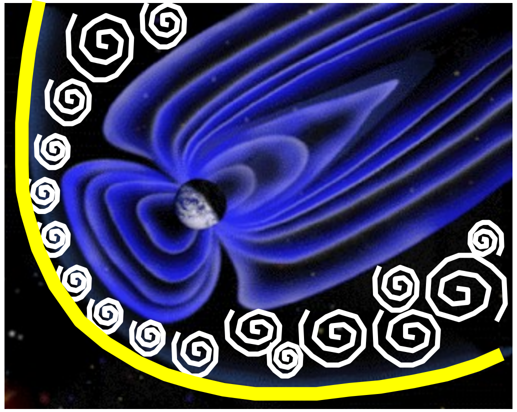
$$\boxed{\delta V_\perp / V_A = \xi \delta B_\perp / B_0}$$

**Monopole ~ force free current, standing structure**




**Dipole ~ two inversed currents, propagates**

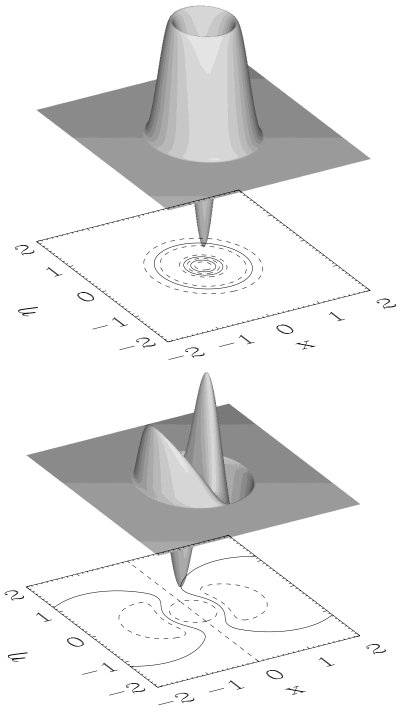


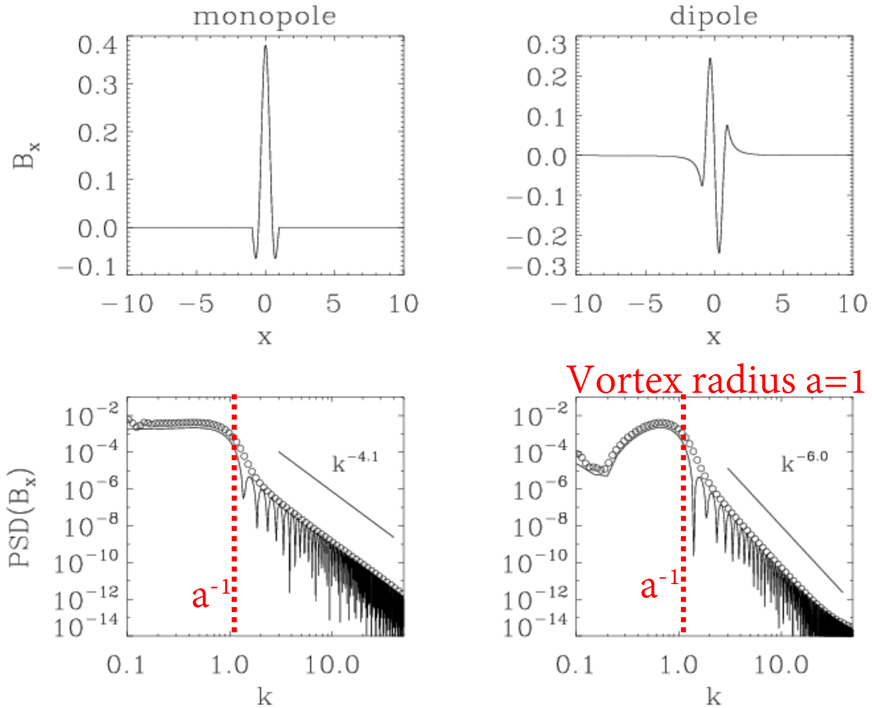



- First time observed in space plasmas in the Earth's magnetosheath [Alexandrova, Mangeney et al., 2004, 2006, JGR] thanks to 4 satellites of Cluster (and to wavelet transform)
- Then signatures of vortices observed in the Saturne's magnetosheath [Alexandrova & Saur 2008]

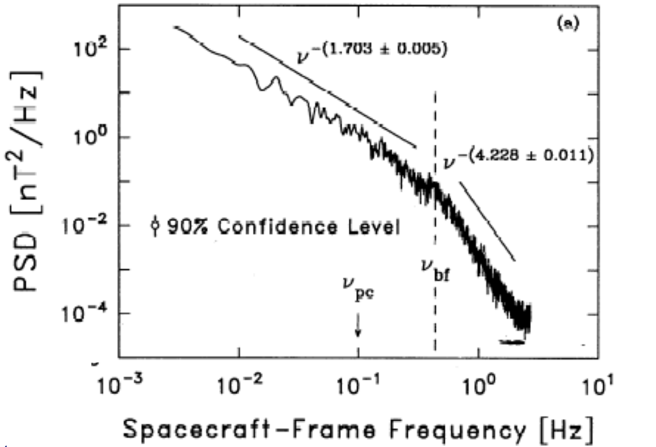
# Spectral properties of Alfvén vortices

[Alexandrova 2008 NPG]



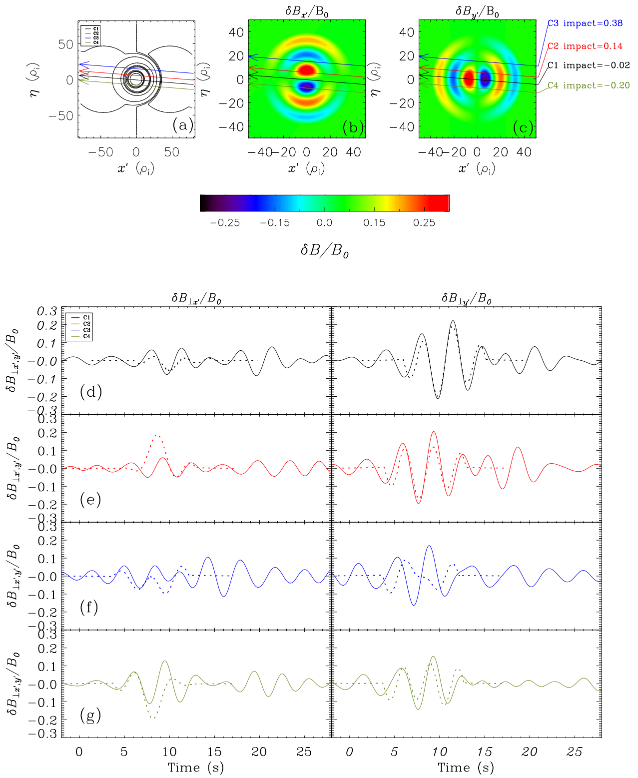




Thus, high amplitude monopolar Alfven vortex present in the signal can explain the steep (-4) spectrum at ion scales in [Leamon 1998], reanalysed by Lion [2016]:

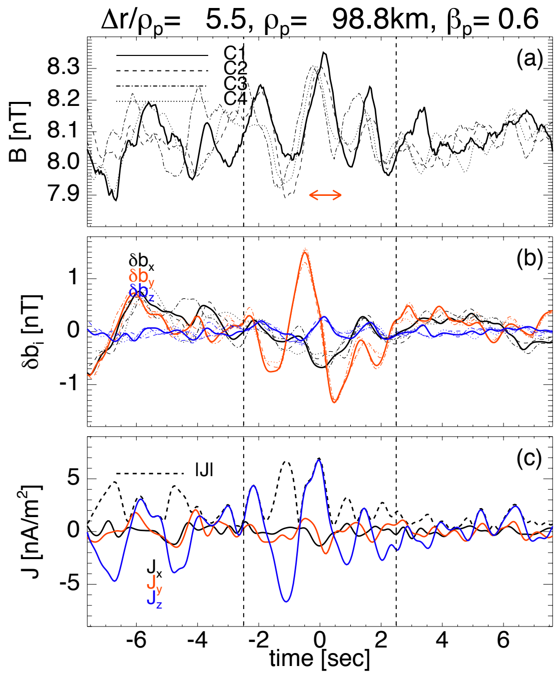


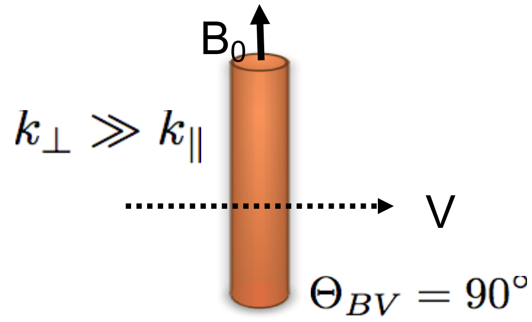

- Spectral knee at $k=a^{-1}$ ; power law spectra above it
- Monopole $\Rightarrow \delta B^2 \sim k^{-4}$ (due to discontinuity of the current)
- Dipole $\Rightarrow \delta B^2 \sim k^{-6}$ (due to discont. of the current derivative)

# Alfven vortices observed in the solar wind with 4 satellites of Cluster




Slow solar wind [Roberts et al. 2016], see also [Perrone et al. 2016]




Fast solar wind [Perrone et al. 2017]

- $k_{perp} >> k_{||}$
- axis aligned with $\mathbf{B}_0$
- convected by the flow

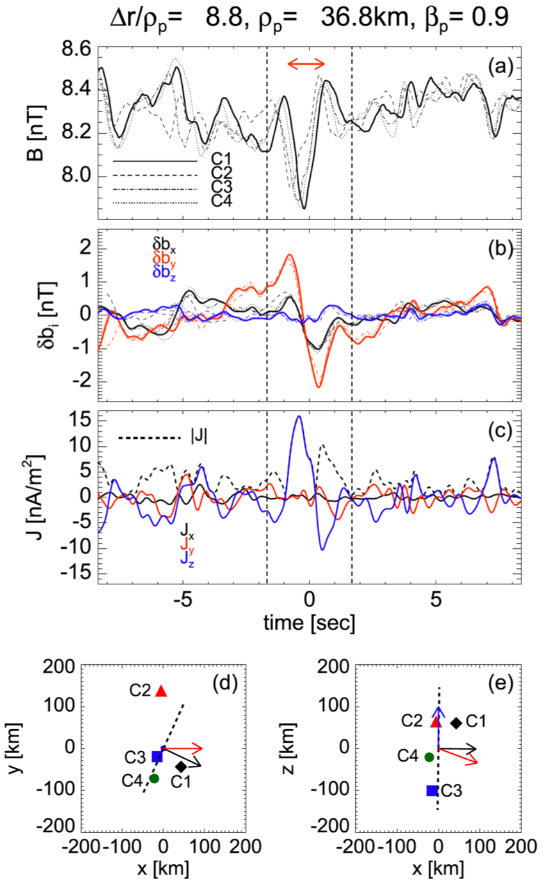
# Other types of structures observed in slow wind

[Perrone et al. 2016]

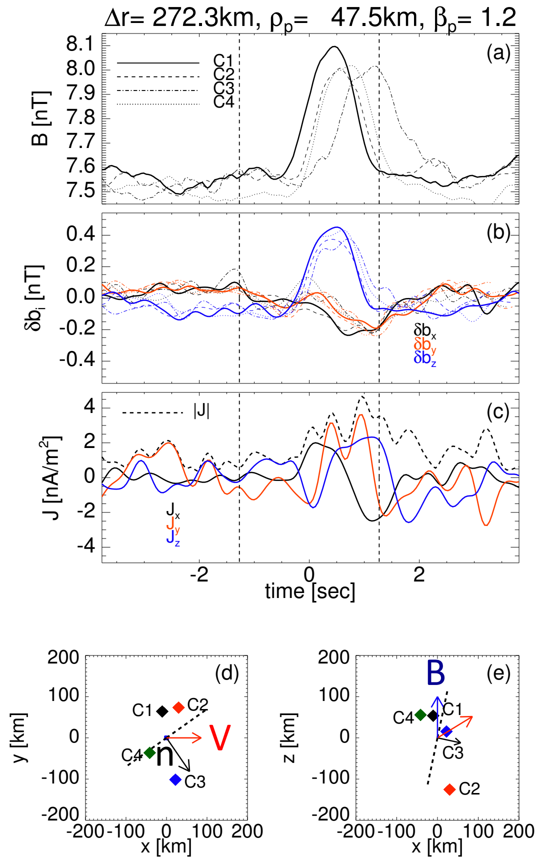
- Current sheets,
- Solitons,
- Shocks,
- Magnetic holes,
- compressible vortices,

**with $k_{perp} >> k_{||}$**

Current sheet $\delta B_{\perp}$

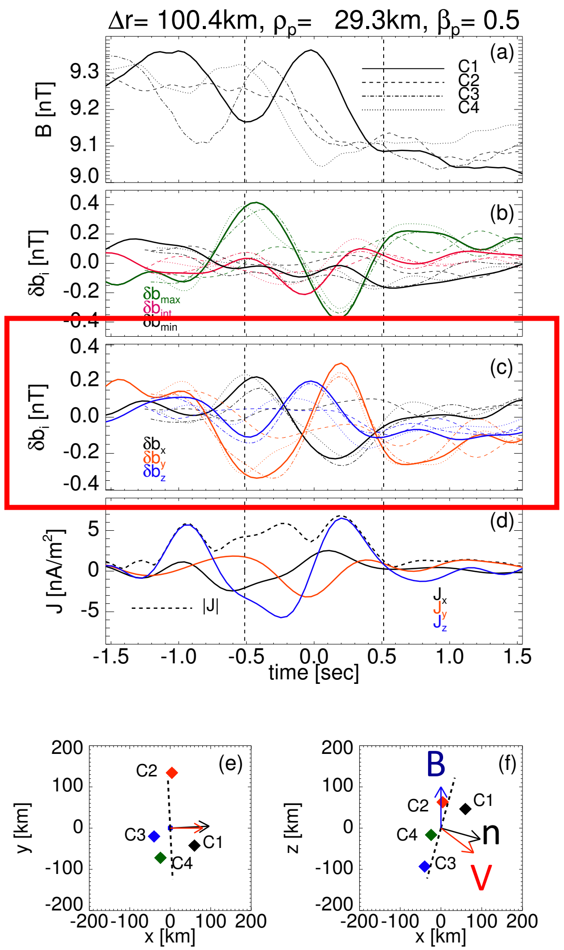



Soliton $\delta B_{||}$



# Compressible vortices (at high ion beta)

[Perrone et al. 2016]

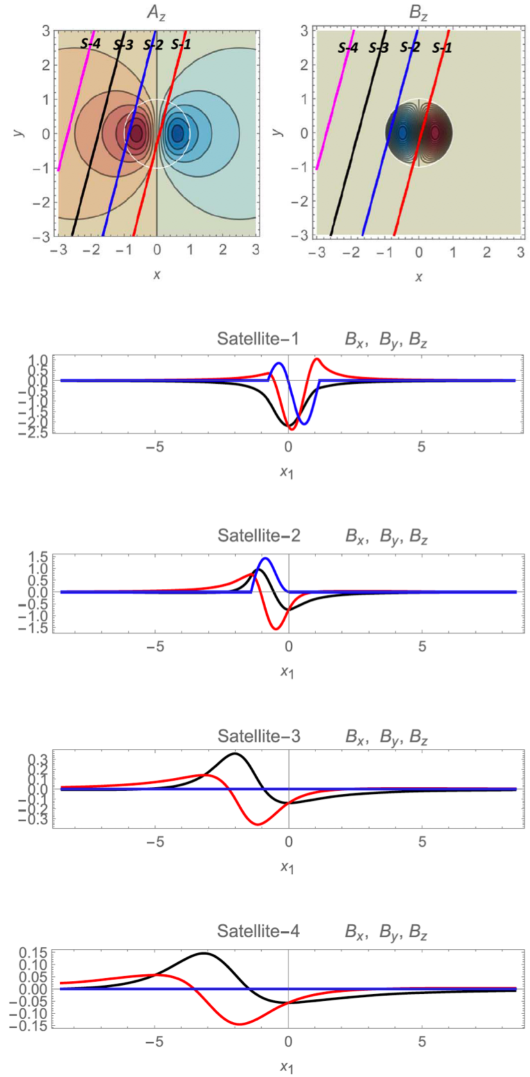



[Jovanovic et al. 2020, APJ]:

Fluid theory of coherent vortices in the space plasmas with anisotropic electron and ion temperatures, and with arbitrary plasma beta.

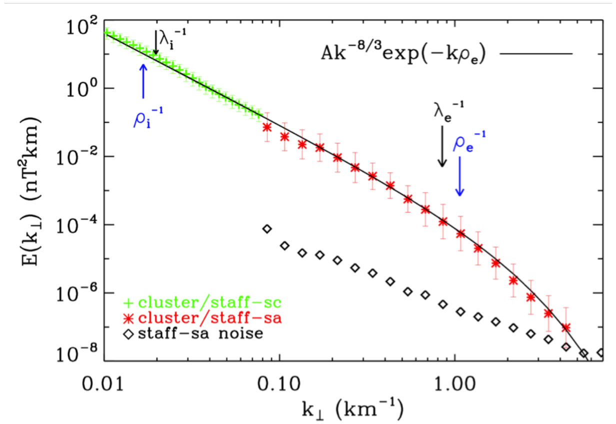
Generalization of Petviashvili & Pokhotelov (1992) vortices including the diamagnetic and finite Larmor radius effects via Braginskii's collisionless stress tensor, and the compressional magnetic component via a generalized pressure balance.

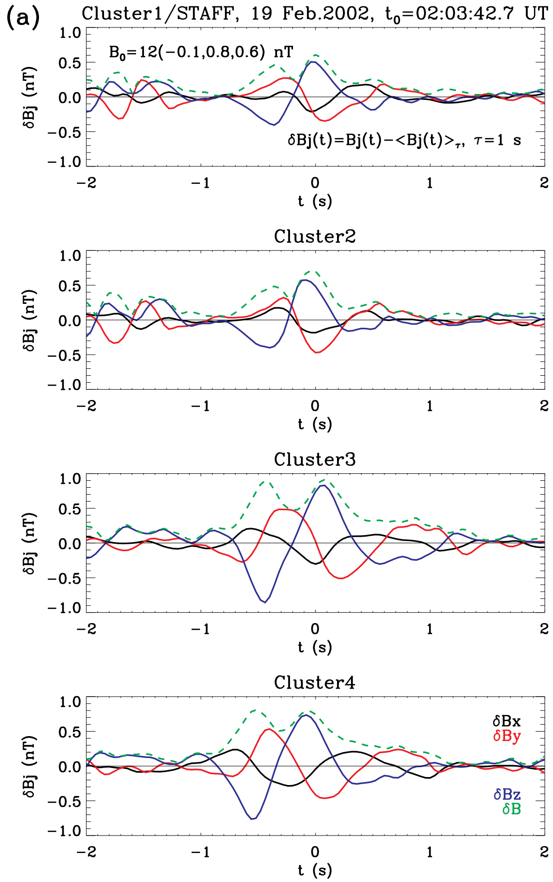
(For more details see the paper and the PSP theory telecon on Nov.19, 2020.)

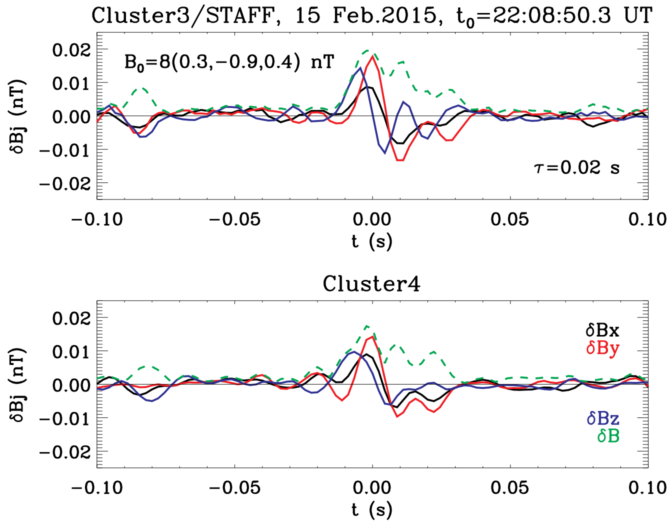


# Sub-ion and electron scales

[Alexandrova et al. 2020, arXiv]




- Magnetic vortex at sub-ion scales
- Vortex duration ~1 s
- Cluster separations ~200 km
- $k_{perp} \gg k_{||}$

- Cluster GI 2015 data:
  - C3-C4 at 7 km distance
  - STAFF in burst mode (360 vec/s)
- Electron scales are resolved for the 1st time in the solar wind in time and in space: duration ~0.05 s, scale ~5 km scale (several $\rho_e$)
- Can we describe them by EMHD non-linear vortices associated with oblique whistlers [Jovanović et al. 2015, Physica Scripta] ?

**Kinetic turbulence is filled with coherent structures ~ vortices**

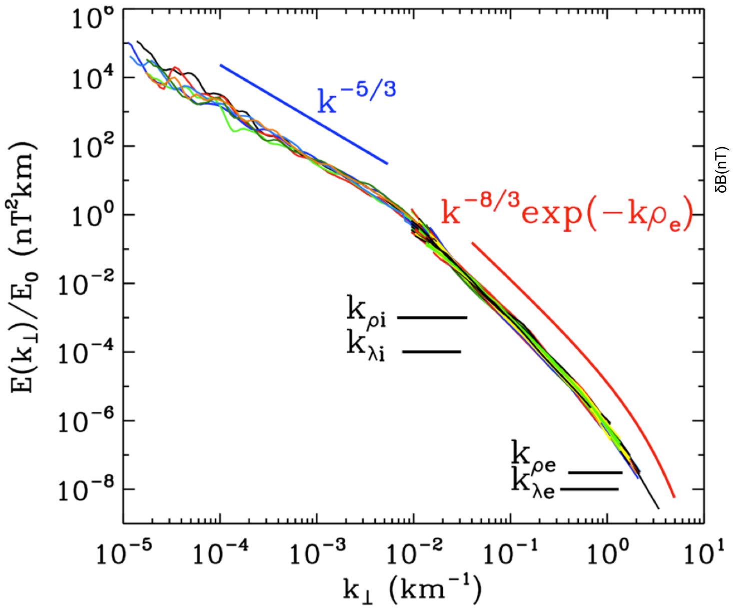
# To summarize

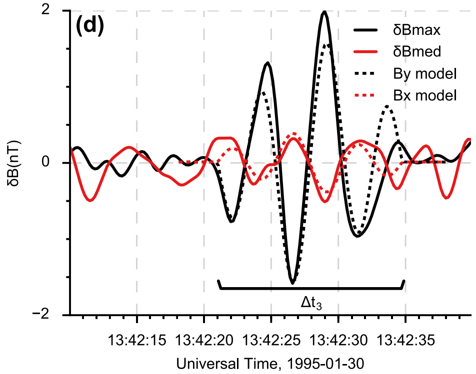
Notwithstanding the complexity of space plasma turbulence:

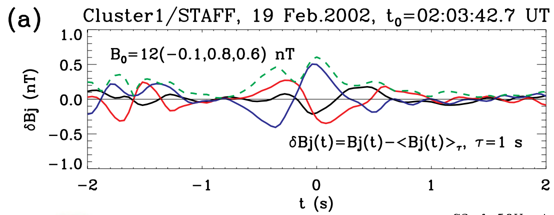
- a certain degree of generality
- similarities with incompressible neutral fluid turbulence

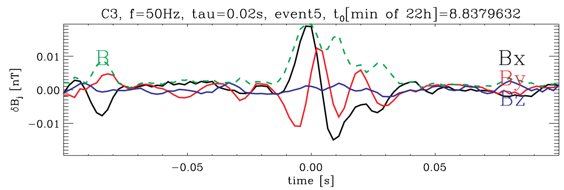
**Results:**

1. We observe a **general spectrum** of magnetic fluctuations up to electron scales ($l_d \sim \rho_e$)
2. Intermittency: not only planar coherent structures, but also **magnetic vortices** up $l_d$



# Open issues & projects

- Topology of coherent structures across the cascade ? More systematic study is needed…
  - under different plasma conditions
  - at different radial distances
- Filling factor ?
- Stability ?
- Interaction of charged particles with coherent structures ⇒ heating of the solar wind ?
  - PHD project of Alexander Vinogradov, IKI-LESIA/SU, 2020-2023
- Energy transfers and dissipation ? Complete parametrisation of turbulent spectrum ?

- New measurements closer to the Sun by Parker Solar Probe and Solar Orbiter will tell us how the picture shown here may change…